III. DEEP WATER RESULTS

A. OPERABILITY INDEX

As we mentioned in the first chapter in this study we considered two criteria when the submarine conducts near surface operations in deep water. One is the number of periscope submergence events per hour, which we can calculate with Equation (29) This number (N_{p1}) was selected as 300, which corresponds to five periscope submergence events per minute. This is an arbitrary number and different numbers could be picked for different operational considerations. Since the same number was used for all cases, the results presented here are representative for all possible choices. The other criterion is the number of sail broachings per hour, which is also calculated from Equation (29). This number (N_{p2}) was selected as one. This places far greater emphasis on sail broaching than periscope submergence since sail broaching is closely related to visual detection.

Now we have the tools to compute the two performance indices defined above in a given seaway. Suppose that the submarine conducts periscope depth operation in a seaway characterized by a significant wave height (Pierson-Moskowitz Wave Spectrum), so that the sea spectrum is defined. For all round the clock boat headings relative to the predominant wave direction for which the operations are to be conducted, a polar plot diagram similar to the one in Figure 6 is prepared. Significant wave heights are represented along the radial direction of the polar plot. The shaded area in the plot shows wave height and wave direction combinations where the selected tactical assessment criterion is exceeded. Letting the polar area of the disk in Figure 6 be A_0 and the subset of

A_0 within which the boat can conduct the operation be A, a performance index characterizing the ability of the boat perform this operation in the specified submarine velocity and depth can be defined as $100(A/A_0)$. Generally a submarine's forward speed ranges from three to twelve knots in periscope depth operations. We used three, five, eight and eleven knots submarine forward speeds, U, in our calculations. Depths, h, beneath the surface were selected from 2.5 to 5 boat diameters measured from the keel up. In computing the above index we could easily take into account the probability of occurrence of a particular sea state and wave heading angle in the area of interest by introducing appropriate weight factors. In this study we assumed that all possible sea-states and wave heading angles are equally probable. In the following sections we discuss the results for both criteria/operability indices and also for the combined criterion/operability index, where both criteria are taken into consideration at the same time.

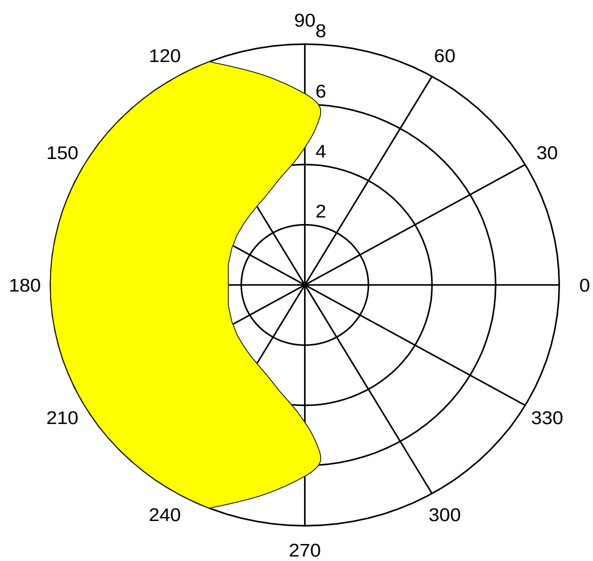

Figure 6. Typical performance assessment of a submarine

B. RESULTS OF PERISCOPE SUBMERGENCE CRITERION

We begin by presenting results with regards to periscope submergence criterion alone. Typical polar plots are shown in Figures 8 through 31. The operability index is presented for different speeds and operating depths in Figures 32 through 41. Based on these results we can draw the following general conclusions:

1. Head seas appear to result in a larger number of expected criterion violations than following seas. This is true regardless of the actual number used in establishing the criterion.
2. For a given sea direction it is possible to reduce criterion violations for higher sea states. This simply means that the motion point moves more in phase with the incoming waves. It should be emphasized, however, that at such high sea states the average wave height may exceed the exposed periscope length. Since the periscope moves in phase with the waves, the operator’s visual horizon may be very small. This situation has been reported in practice and although the criterion is not exceeded, operations are very difficult to conduct. Such a situation can only be analyzed with proper visual simulation studies.
3. An optimum operating depth can be found which maximizes the expected number of periscope submergence events. This depth depends on the forward speed, but it appears to be a weak function of speed.

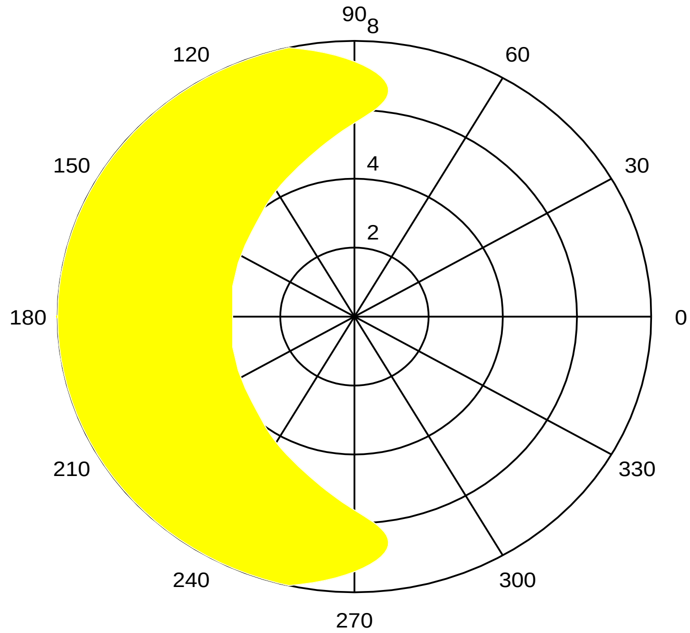

Figure 8. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=2.5D

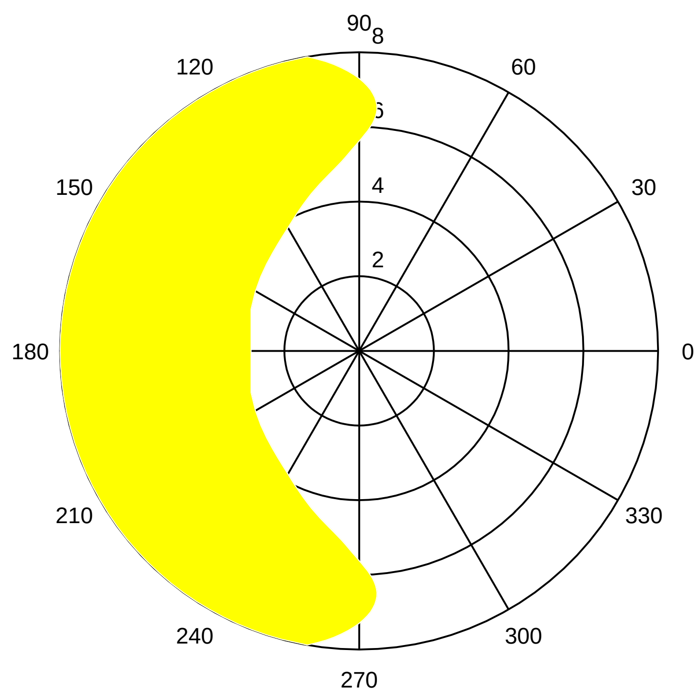

Figure 9. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=2.5D

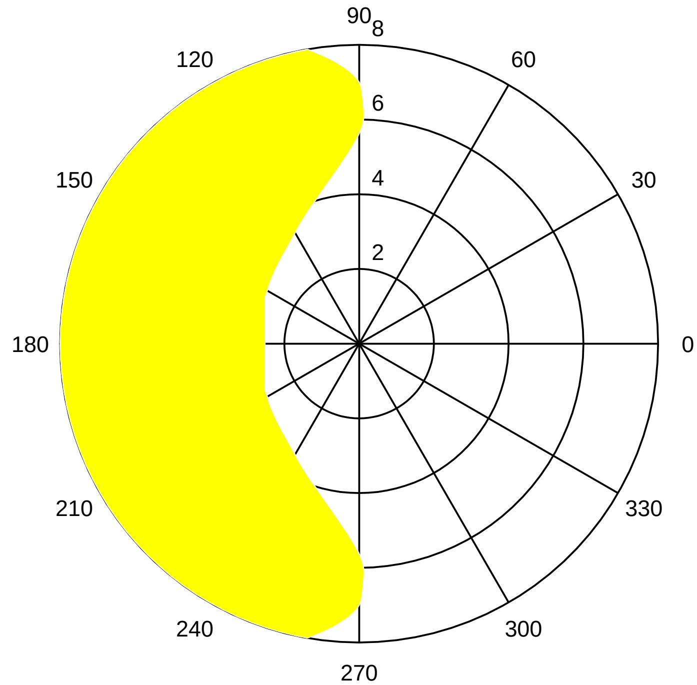

Figure 10. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=2.5D

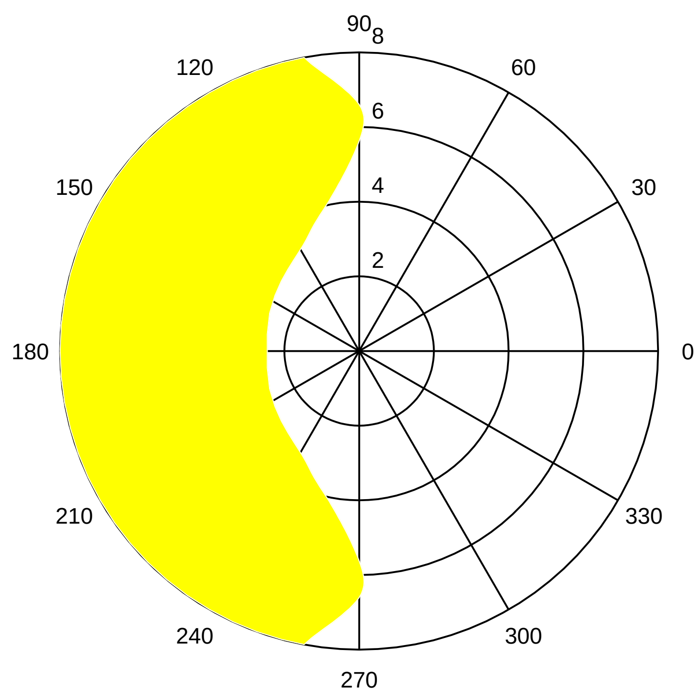

Figure 11. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=2.5D

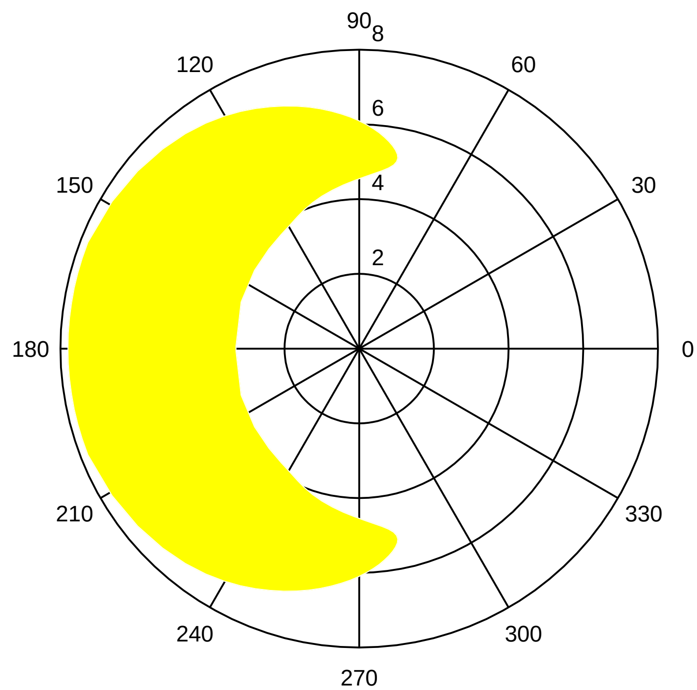

Figure 12. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=3D

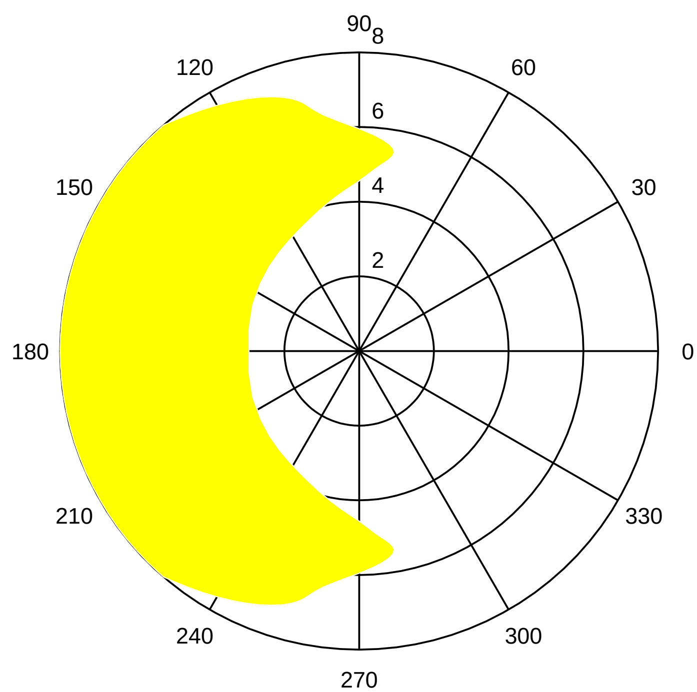

Figure 13. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=3D

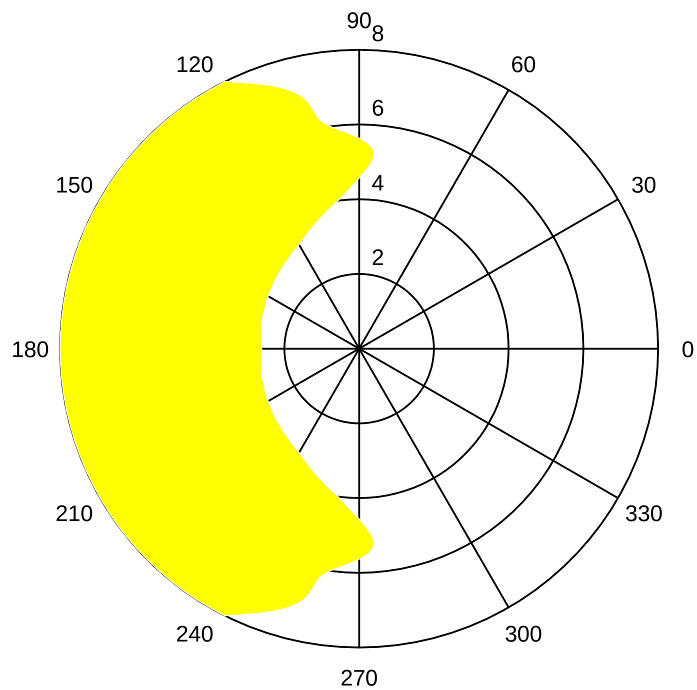

Figure 14. Sea state-polar plot, showing SOE for a submarine *U*=8 Knots, *h*=3*D*

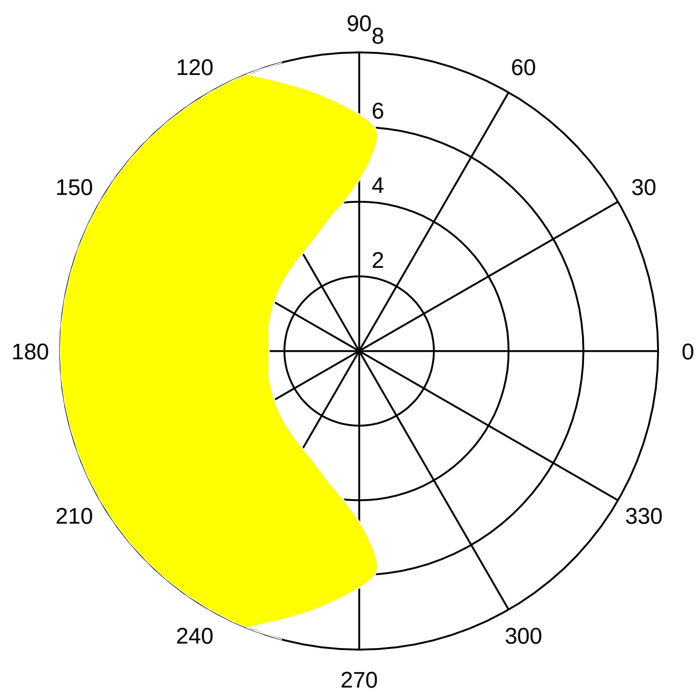

Figure 15. Sea state-polar plot, showing SOE for a submarine *U*=11 Knots, *h*=3*D*

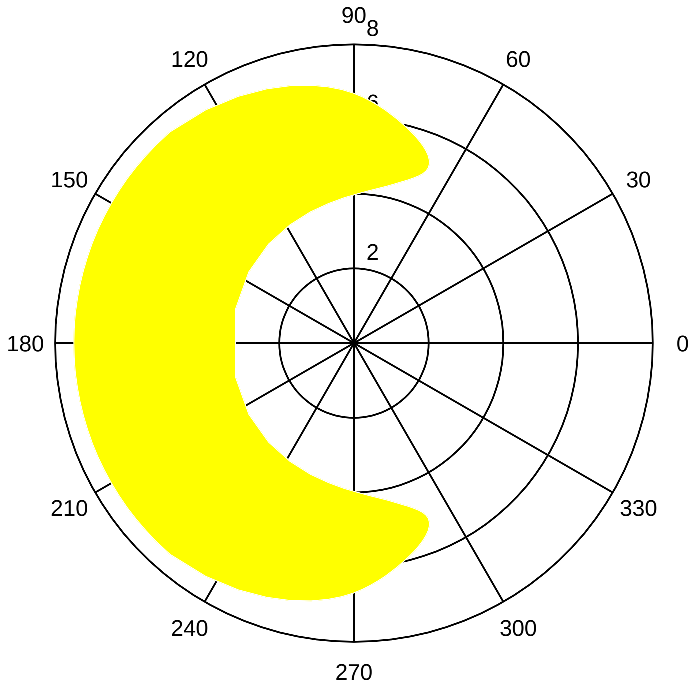

Figure 16. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=3.5D

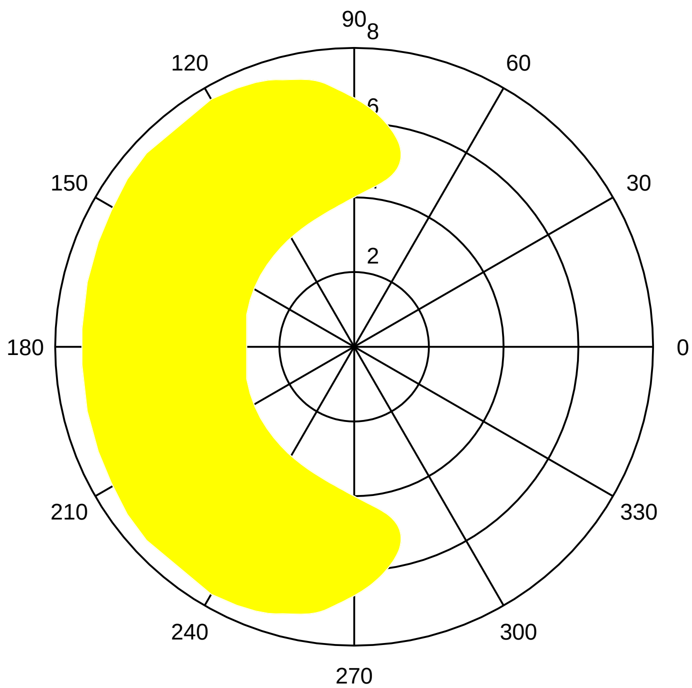

Figure 17. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=3.5D

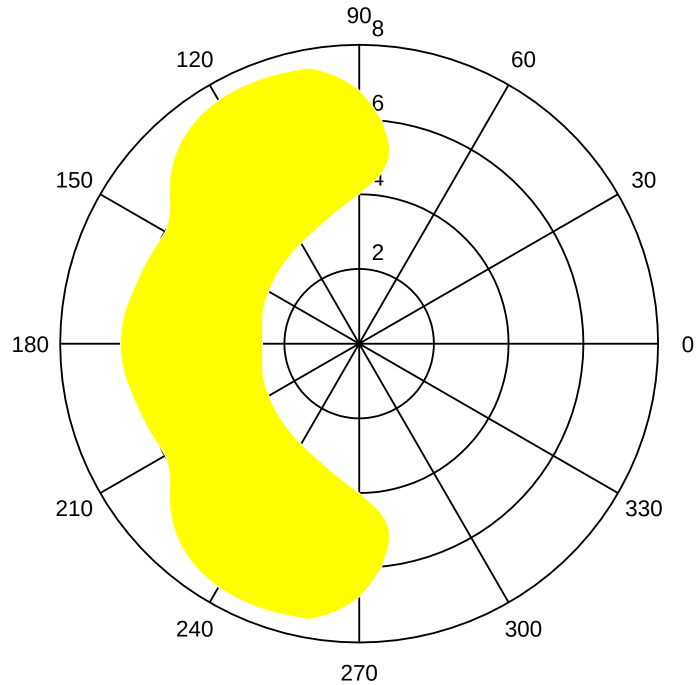

Figure 18. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=3.5D

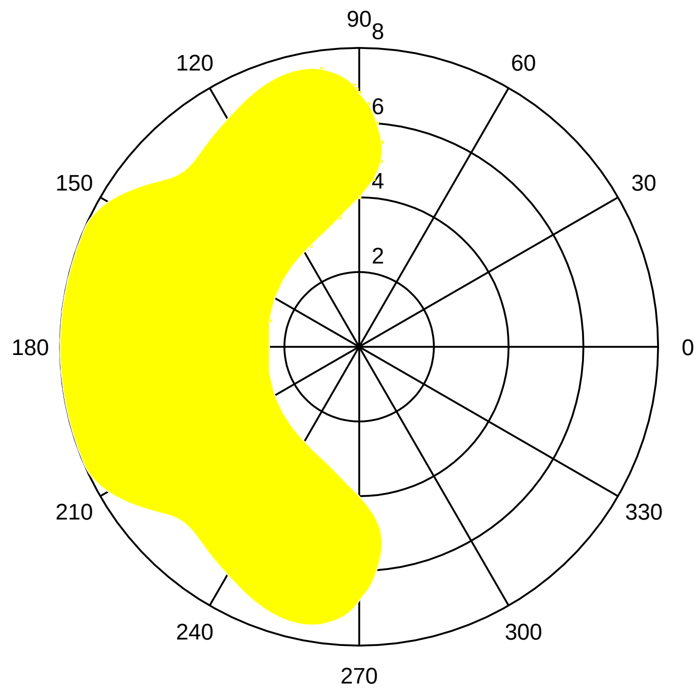

Figure 19. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=3.5D

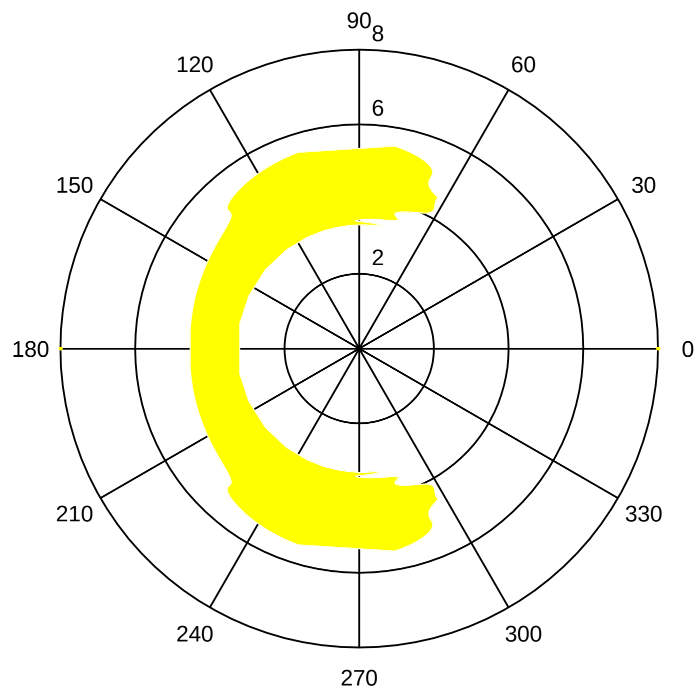

Figure 20. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=4D

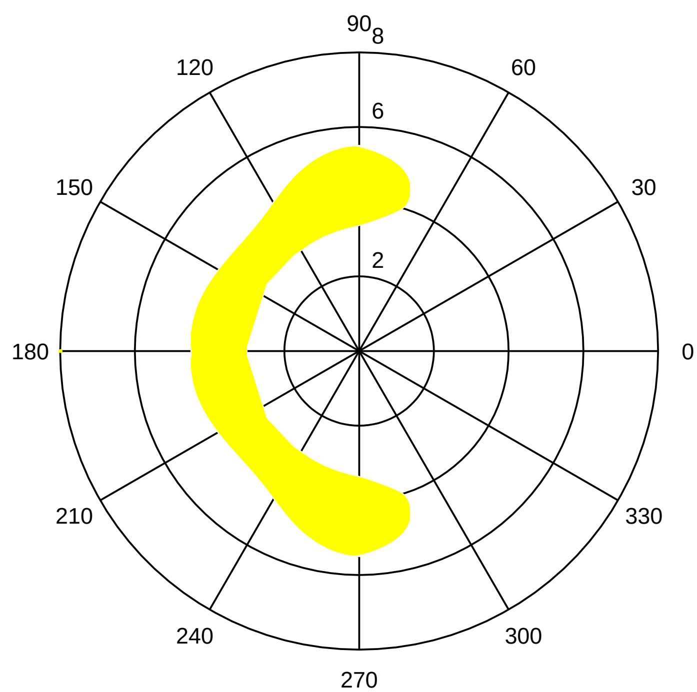

Figure 21. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=4D

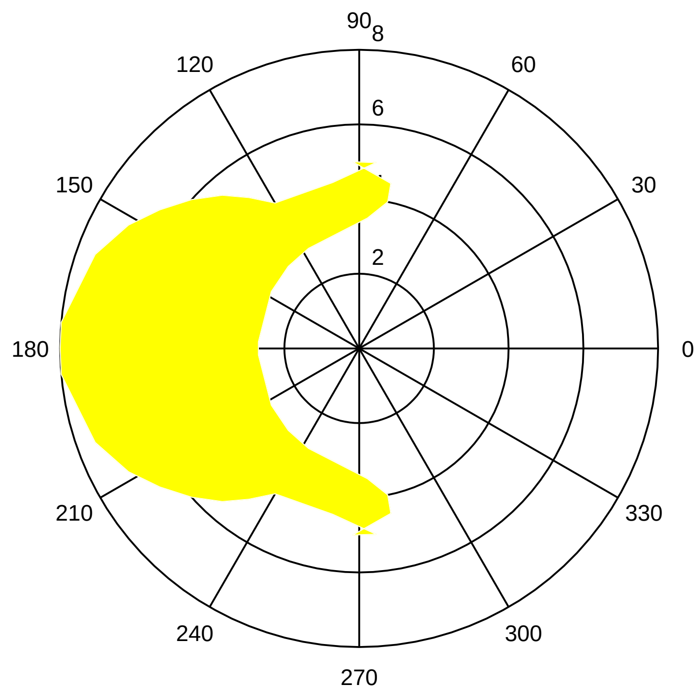

Figure 22. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=4D

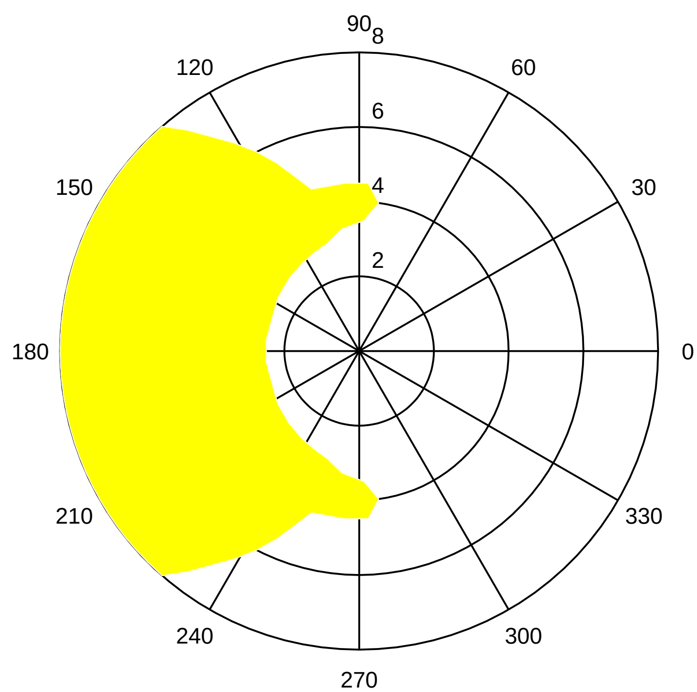

Figure 23. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=4D

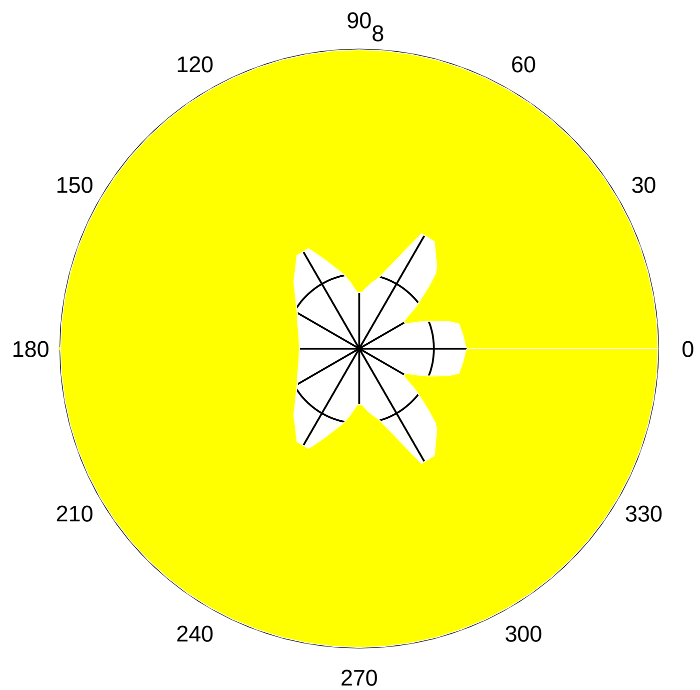

Figure 24. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=4.5D

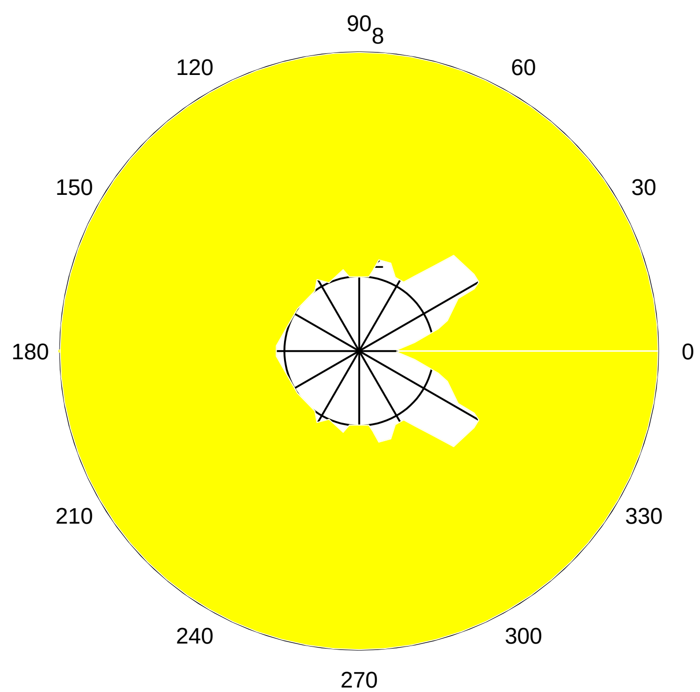

Figure 25. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=4.5D

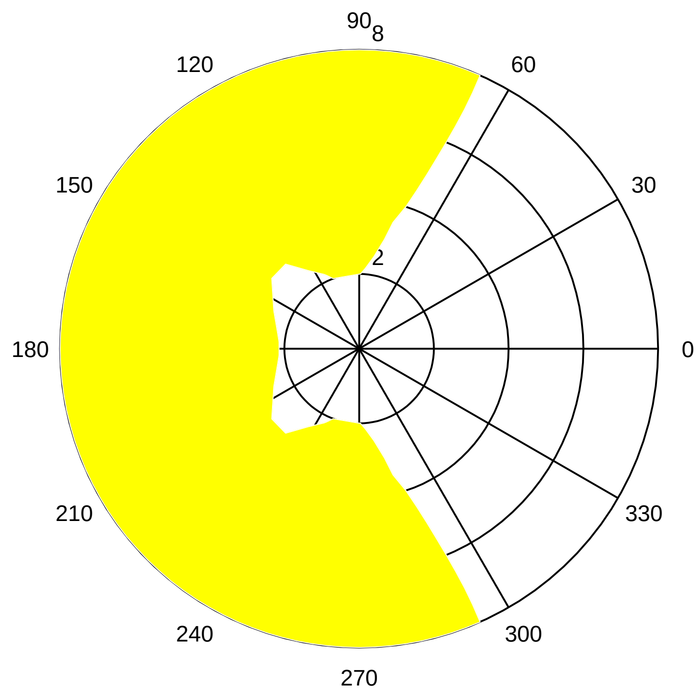

Figure 26. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=4.5D

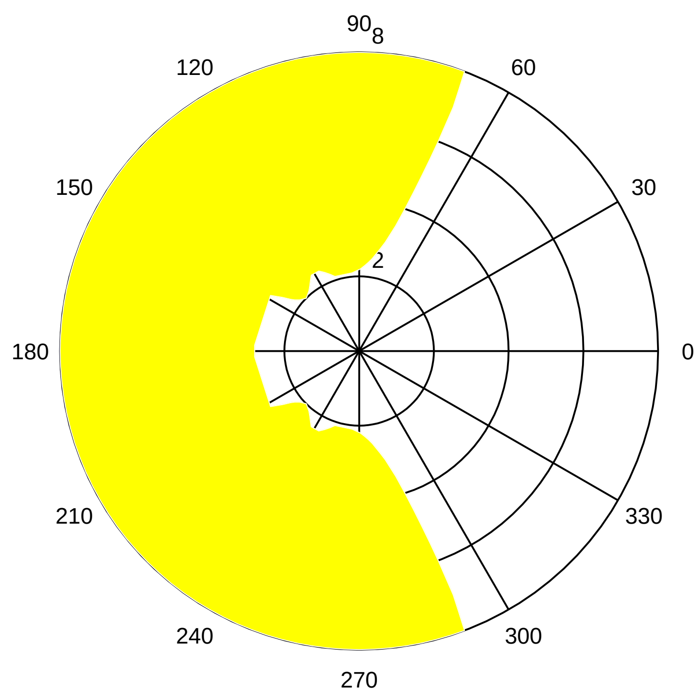

Figure 27. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=4.5D

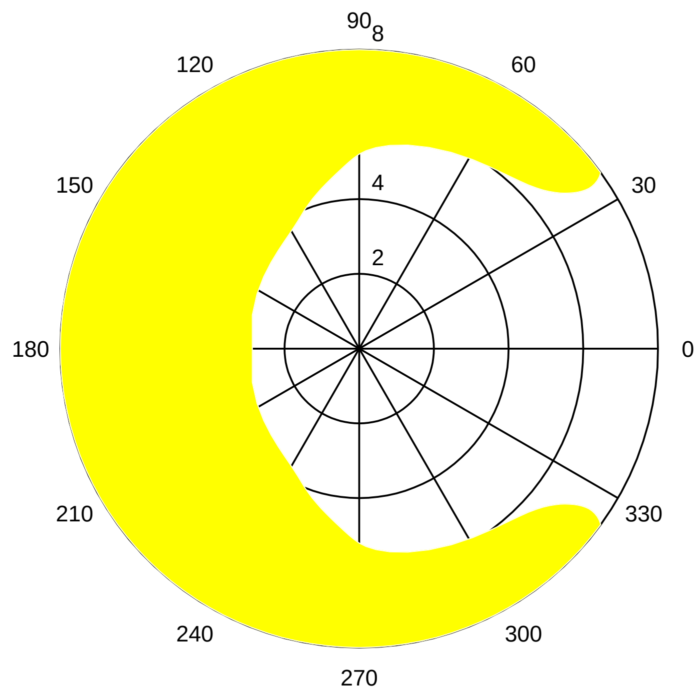

Figure 28. Sea state-polar plot, showing SOE for a submarine *U*=3 Knots, *h*=5*D*

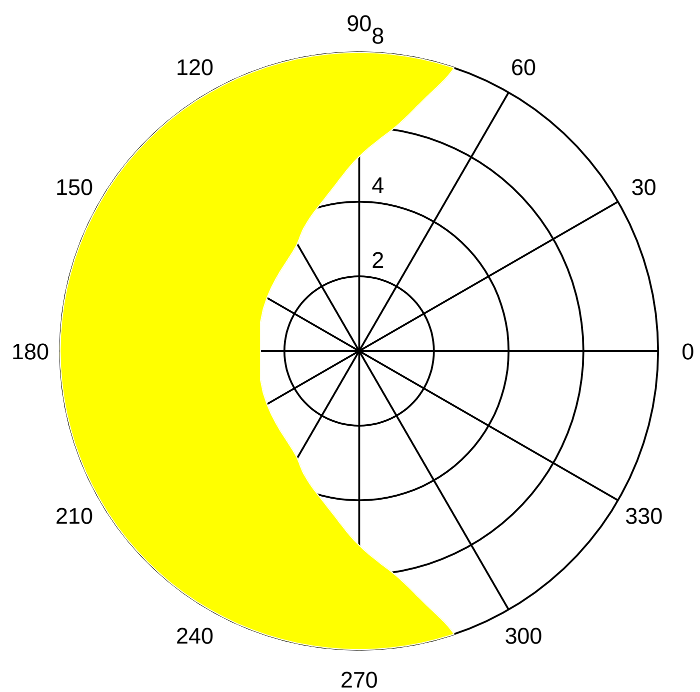

Figure 29. Sea state-polar plot, showing SOE for a submarine *U*=5 Knots, *h*=5*D*

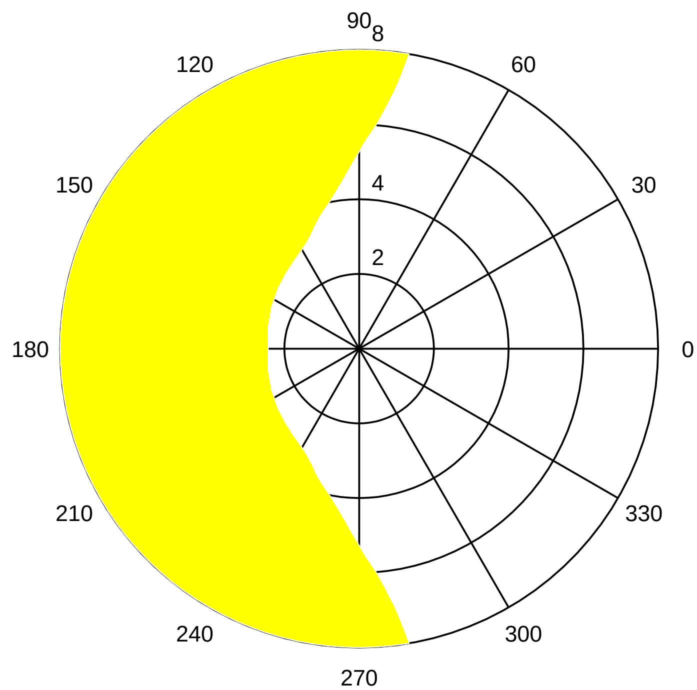

Figure 30. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=5D

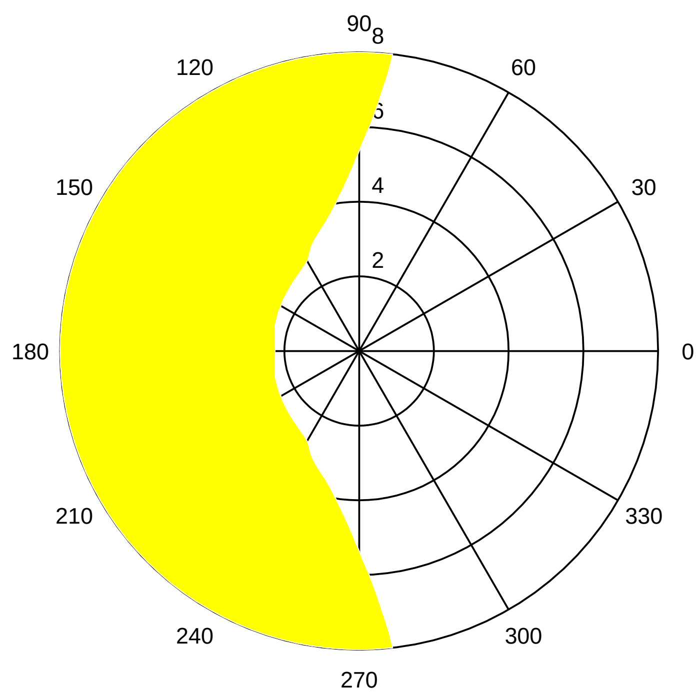

Figure 31. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=5D

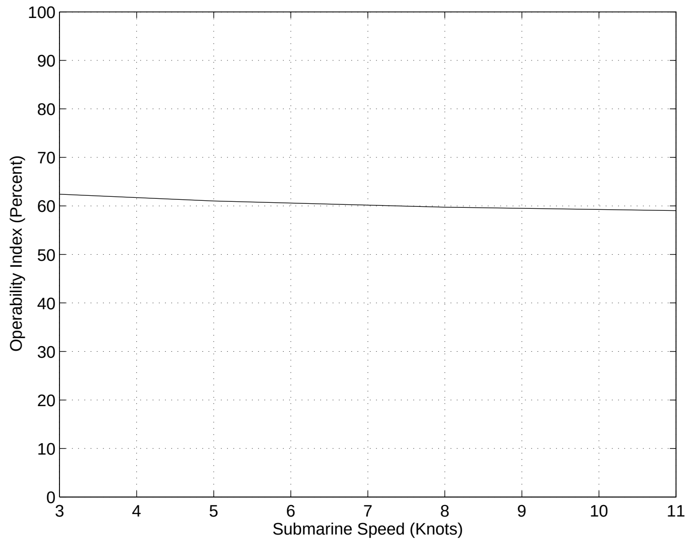

Figure 32. OI vs. Submarine Speed Plot at 2.5*D* depth

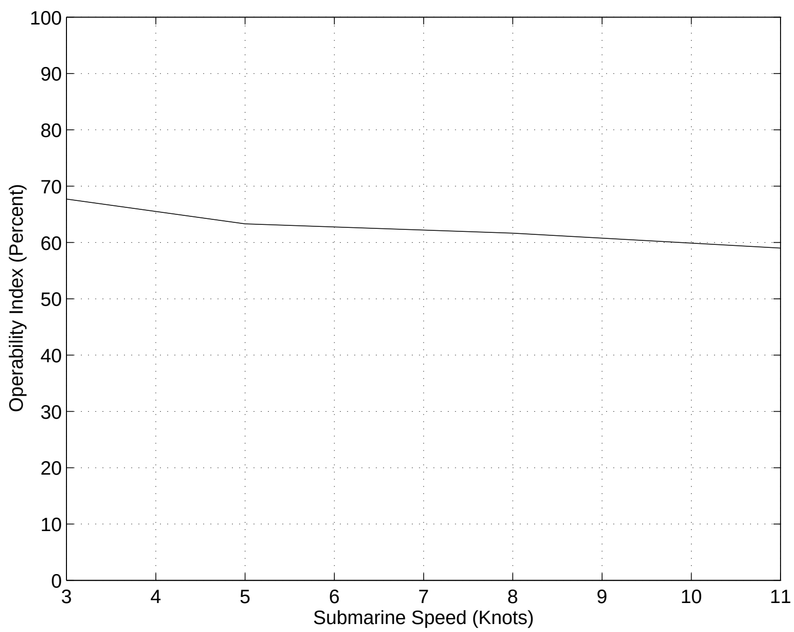

Figure 33. OI vs. Submarine Speed Plot at 3*D* depth

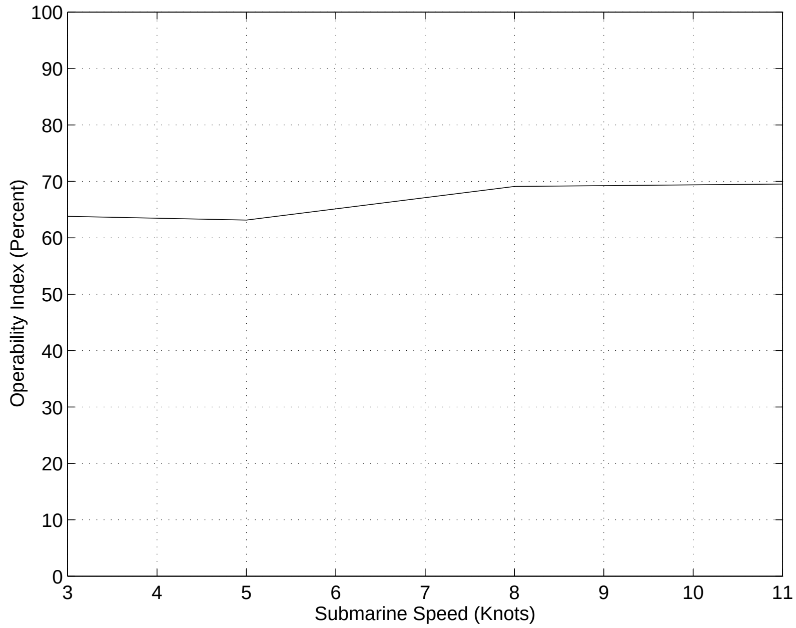

Figure 34. OI vs. Submarine Speed Plot at 3.5*D* depth

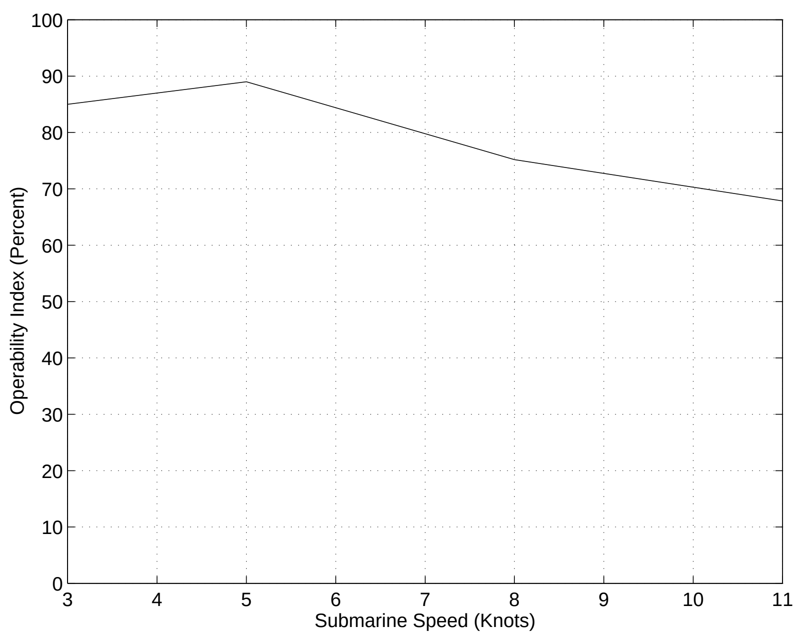

Figure 35. OI vs. Submarine Speed Plot at 4*D* depth

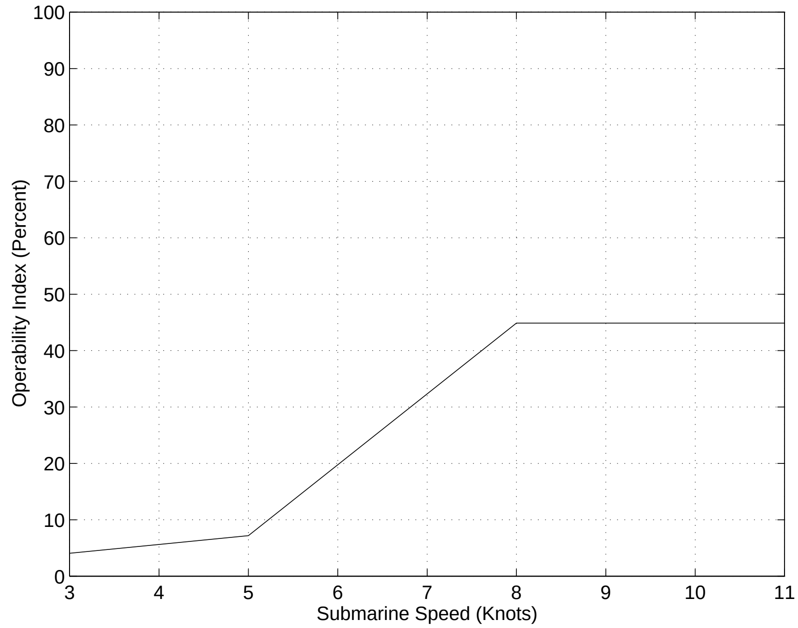

Figure 36. OI vs. Submarine Speed Plot at 4.5*D* depth

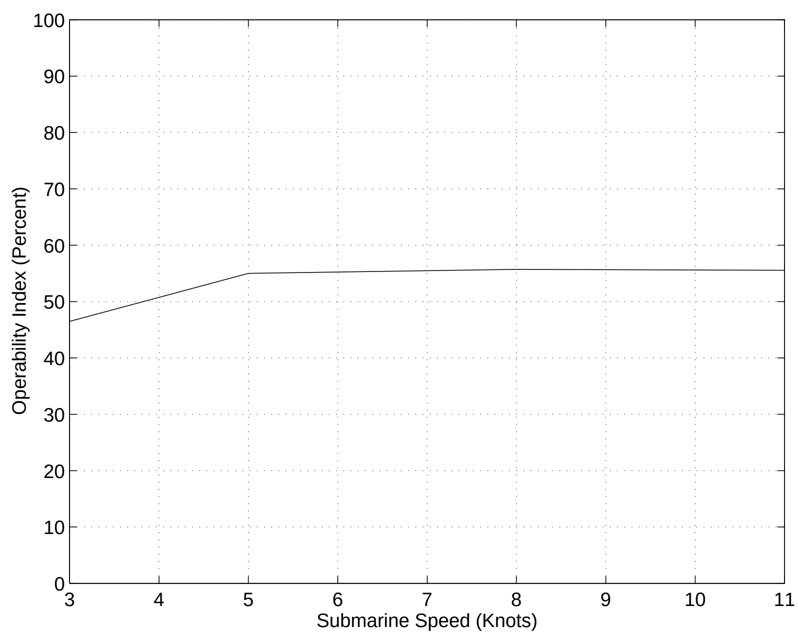

Figure 37. OI vs. Submarine Speed Plot at 5*D* depth

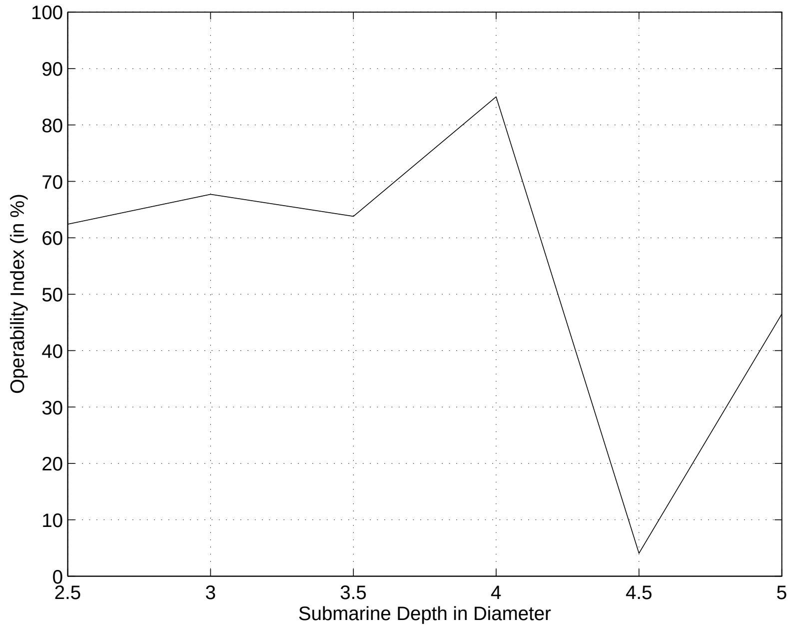

Figure 38. OI vs. Submarine Depth Plot in Submarine Diameters at 3 Knots

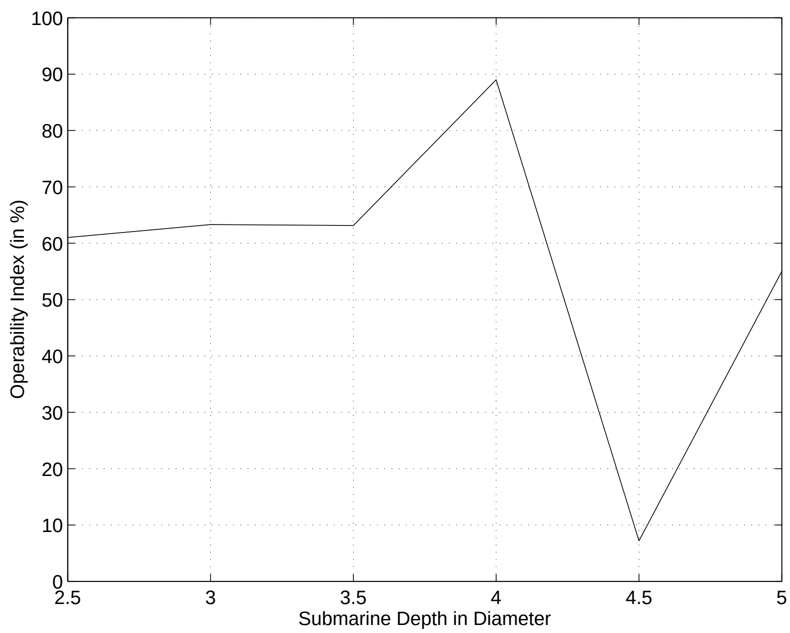

Figure 39. OI vs. Submarine Depth Plot in Submarine Diameters at 5 Knots

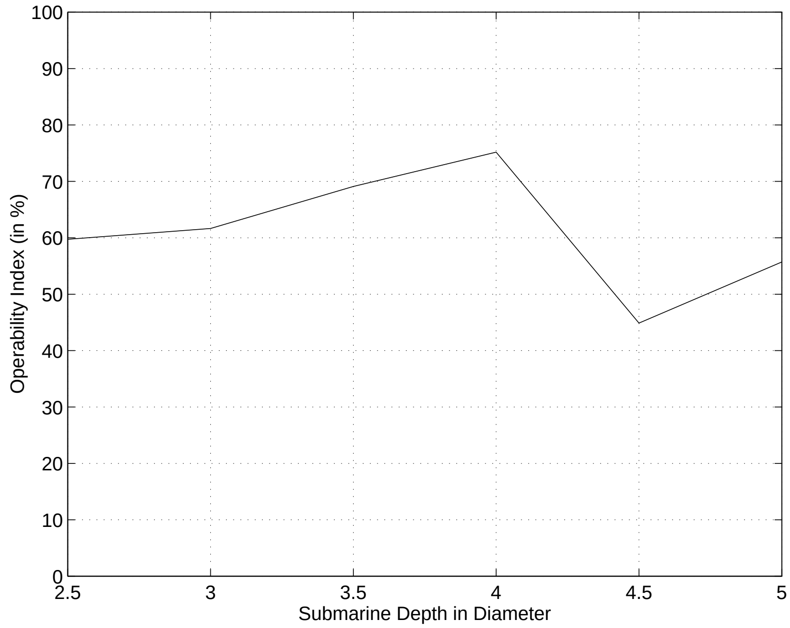

Figure 40. OI vs. Submarine Depth Plot in Submarine Diameters at 8 Knots

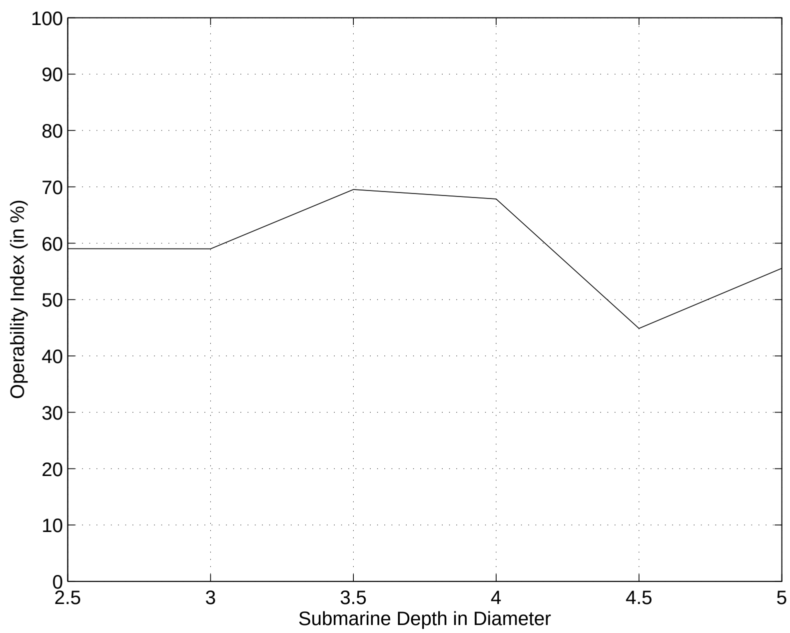

Figure 41. OI vs. Submarine Depth Plot in Submarine Diameters at 11 Knots

C. RESULTS OF SAIL BROACHING CRITERION

Typical polar plots for the sail broaching criterion event are shown in Figures 42 through 57. The operability index is presented for different speeds and operating depths in Figures 58 through 66. Based on these results we can draw the following general conclusions:

1. There does not appear to be a consistent dependence of the operability index on sea direction. Certain sea directions, however, greatly reduce the operability index for some speed/depth combinations.
2. For a given sea direction, higher sea states correspond to smaller operability indices.
3. The operability index does not vary significantly with speed or depth, and it generally increases with increasing depth..

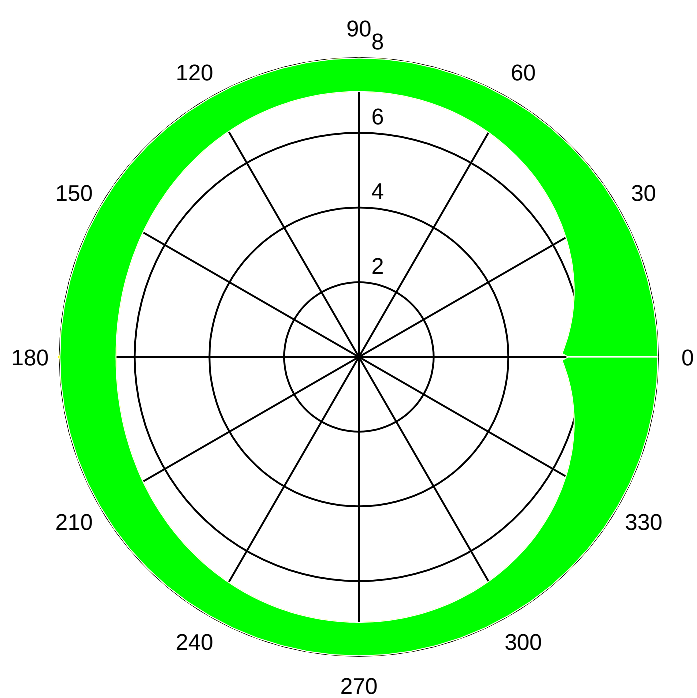

Figure 42. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=2.5D

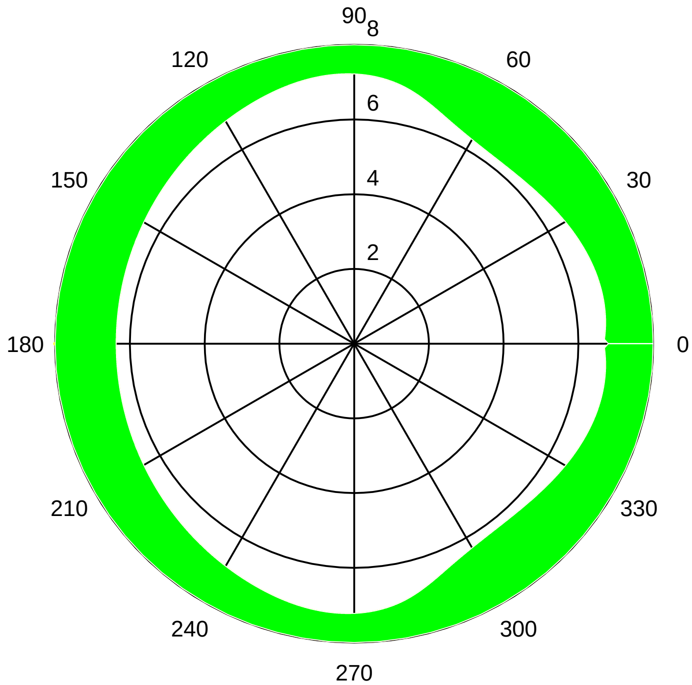

Figure 43. Sea state-polar plot, showing SOE for a submarine *U*=5 Knots, *h*=2.5*D*

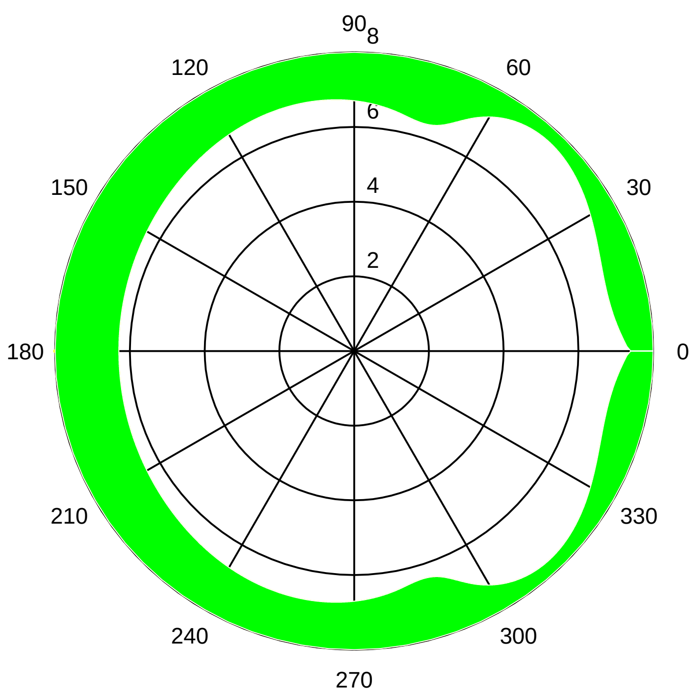

Figure 44. Sea state-polar plot, showing SOE for a submarine *U*=8 Knots, *h*=2.5*D*

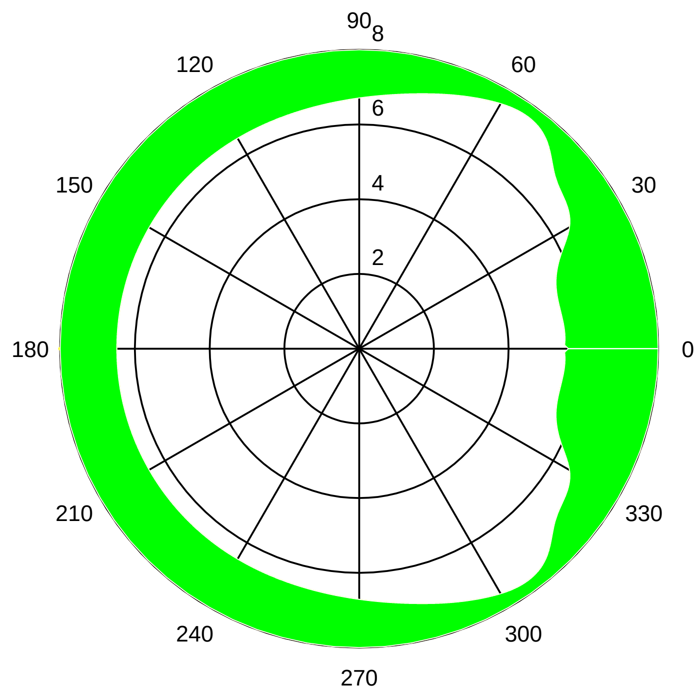

Figure 45. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=2.5D

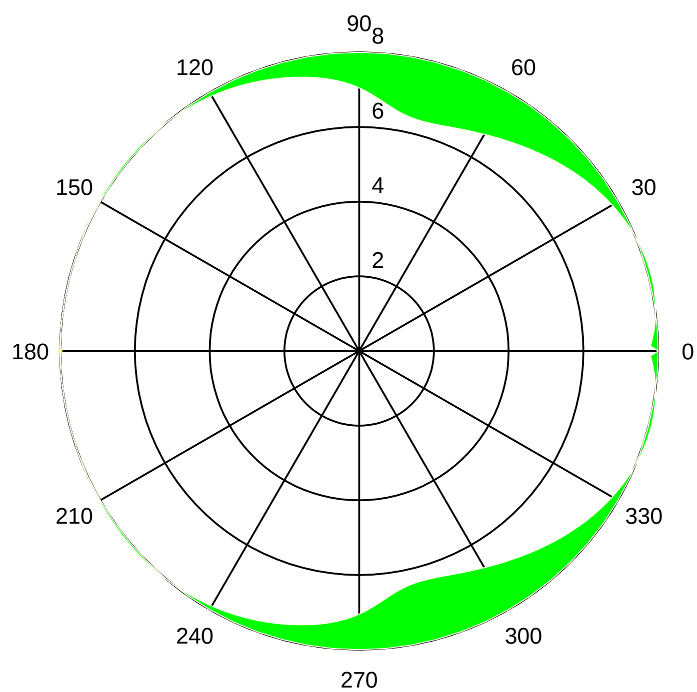

Figure 46. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=3D

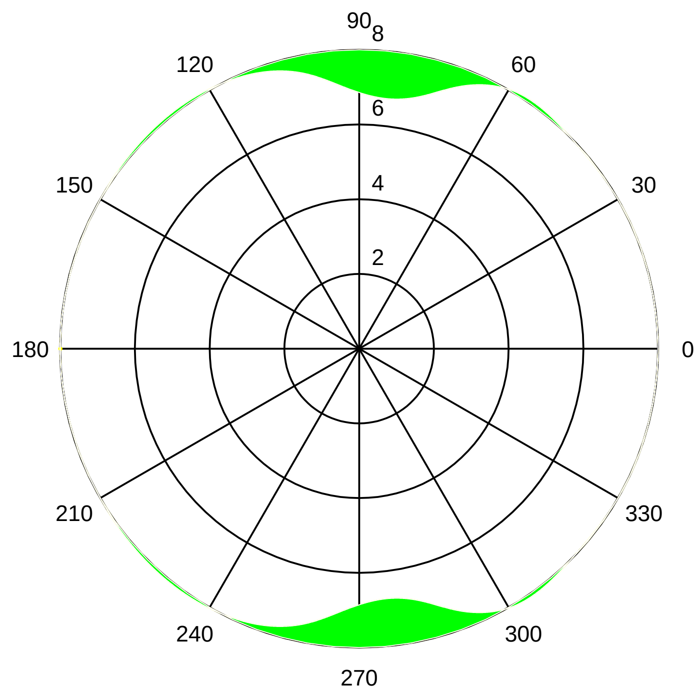

Figure 47. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=3D

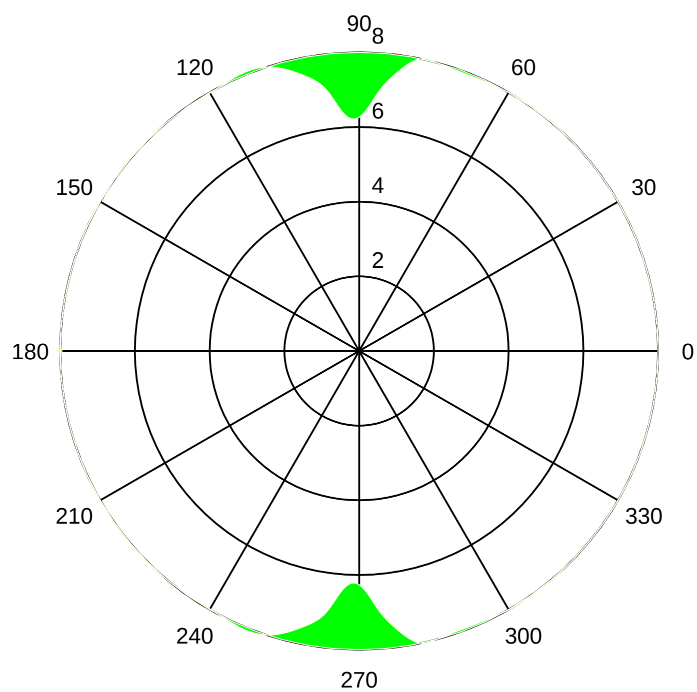

Figure 48. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=3D

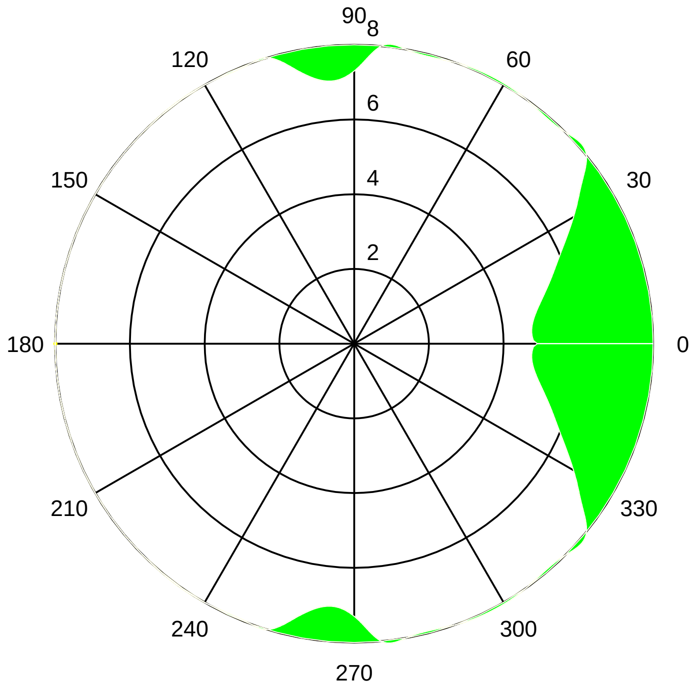

Figure 49. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=3D

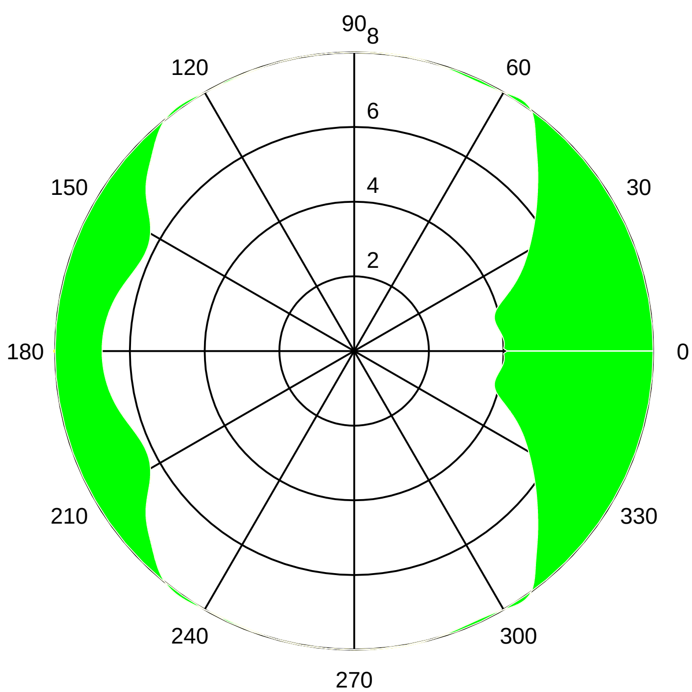

Figure 50. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=3.5D

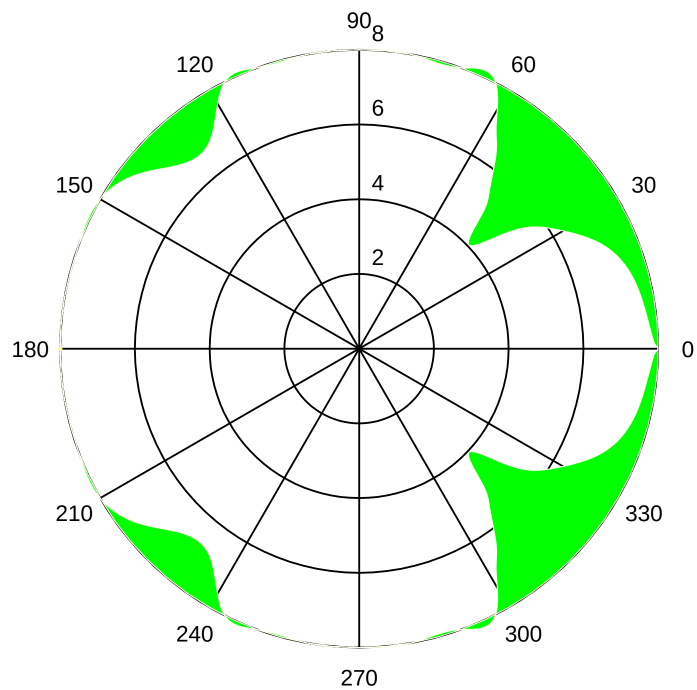

Figure 51. Sea state-polar plot, showing SOE for a submarine *U*=11 Knots, *h*=3.5*D*

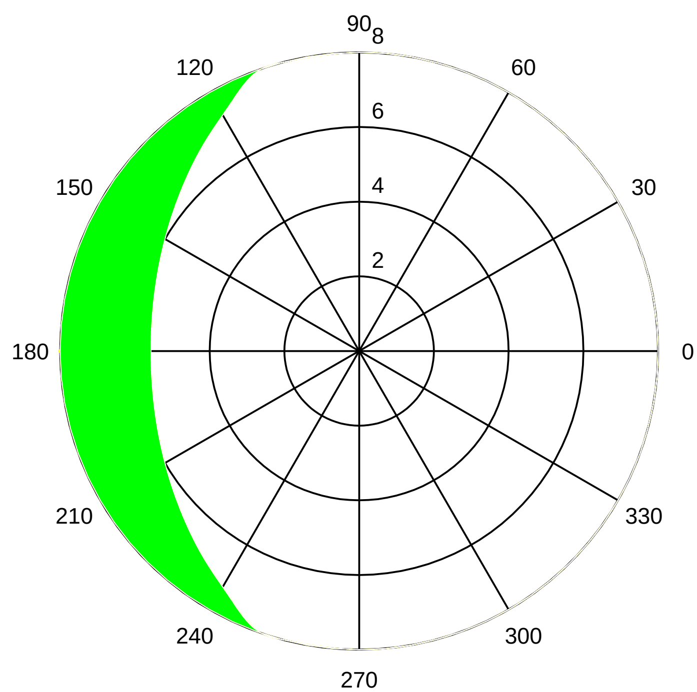

Figure 52. Sea state-polar plot, showing SOE for a submarine *U*=3 Knots, *h*=4*D*

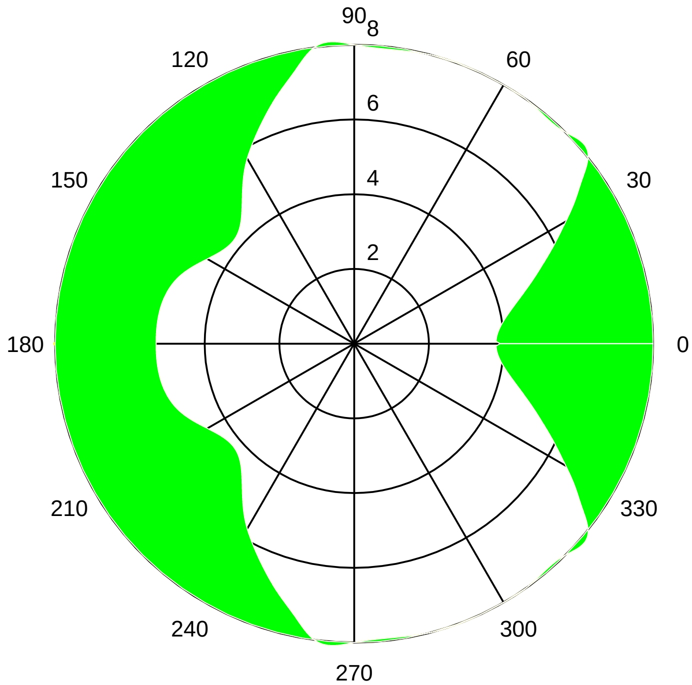

Figure 53. Sea state-polar plot, showing SOE for a submarine *U*=5 Knots, *h*=4*D*

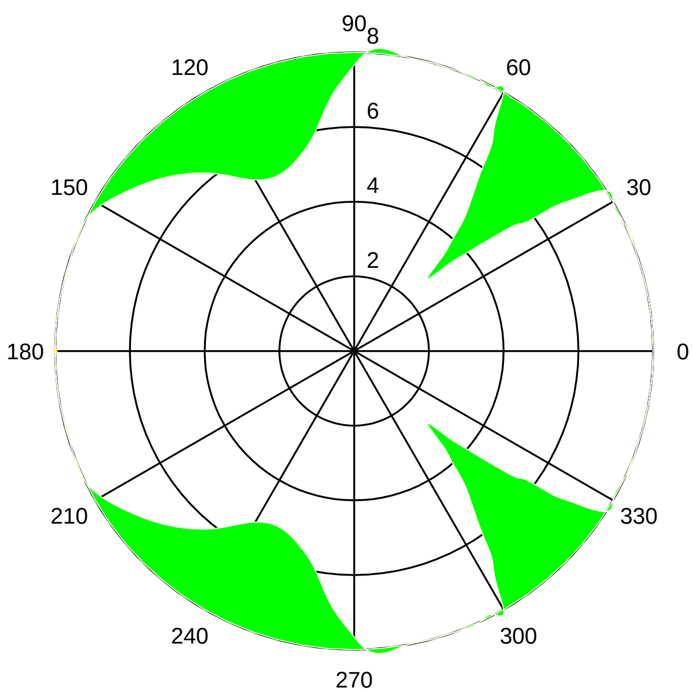

Figure 54. Sea state-polar plot, showing SOE for a submarine *U*=8 Knots, *h*=4*D*

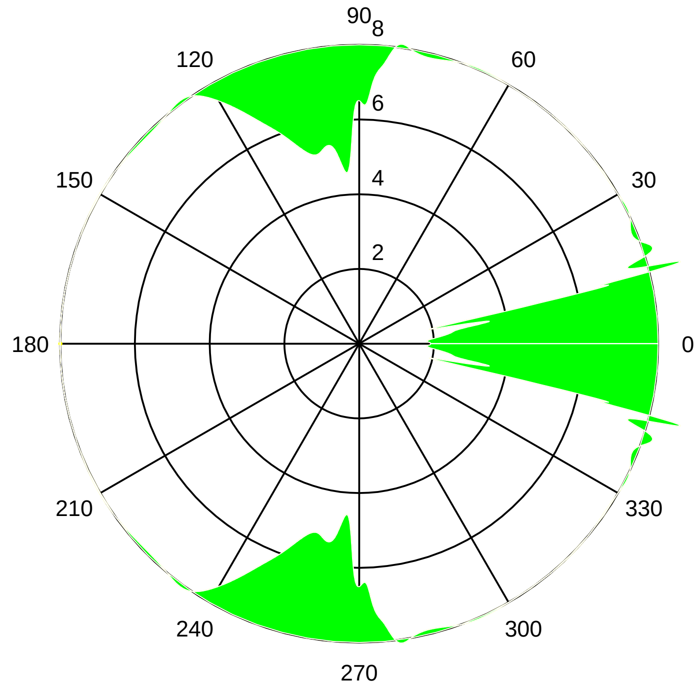

Figure 55. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=4D

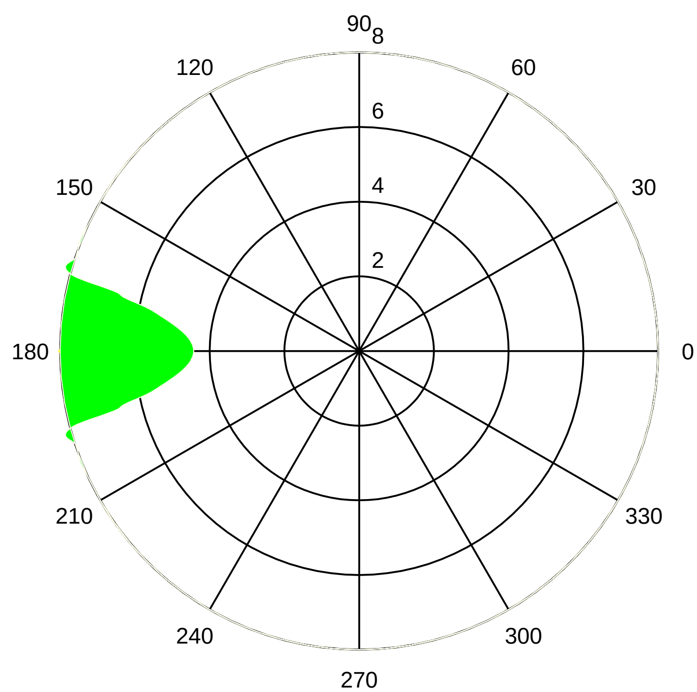

Figure 56. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=4.5D

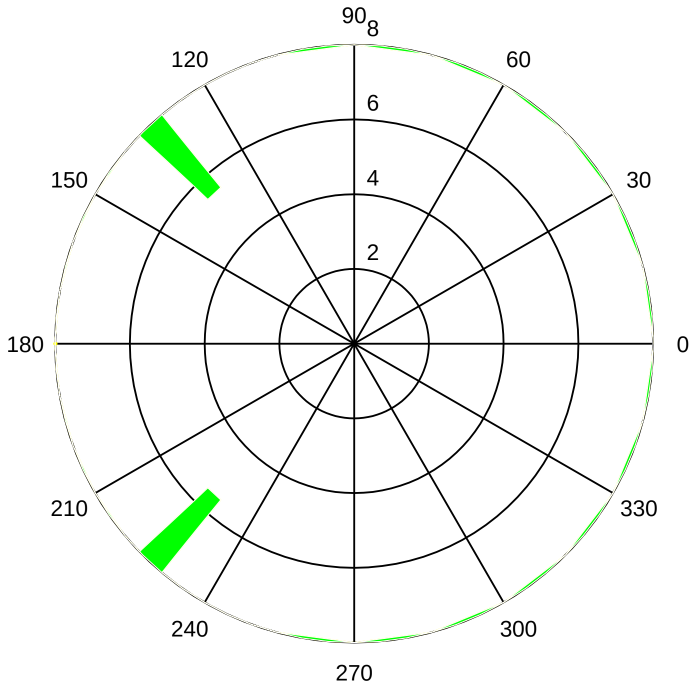

Figure 57. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=4.5D

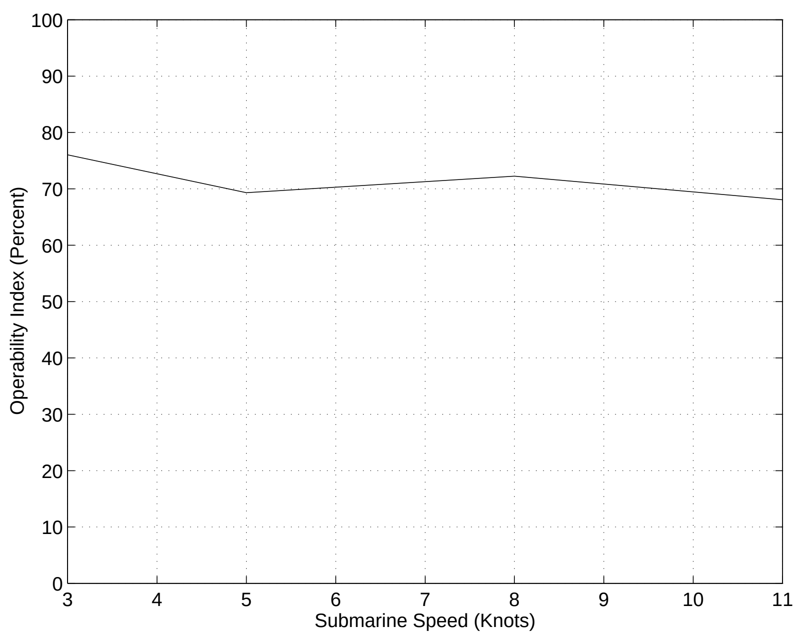

Figure 58. OI vs. Submarine Speed Plot at 2.5D depth

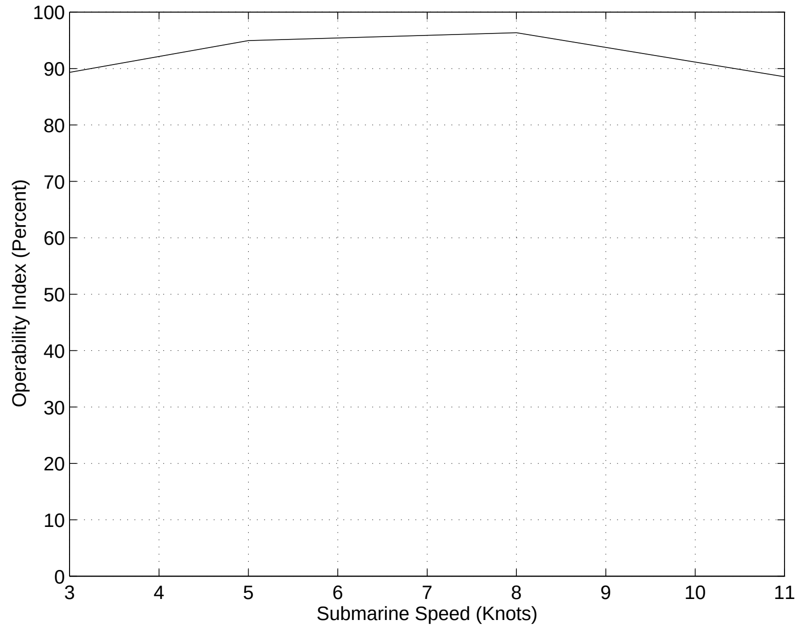

Figure 59. OI vs. Submarine Speed Plot at 3*D* depth

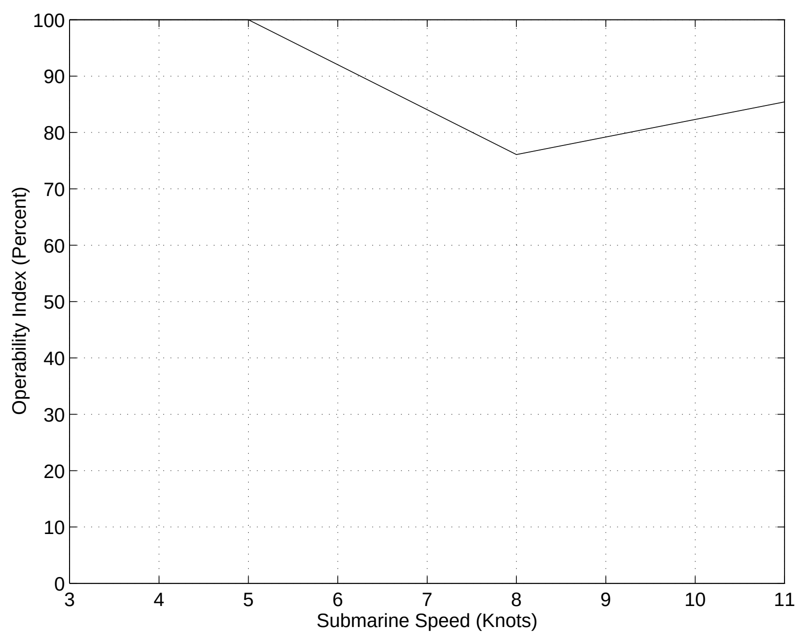

Figure 60. OI vs. Submarine Speed Plot at 3.5*D* depth

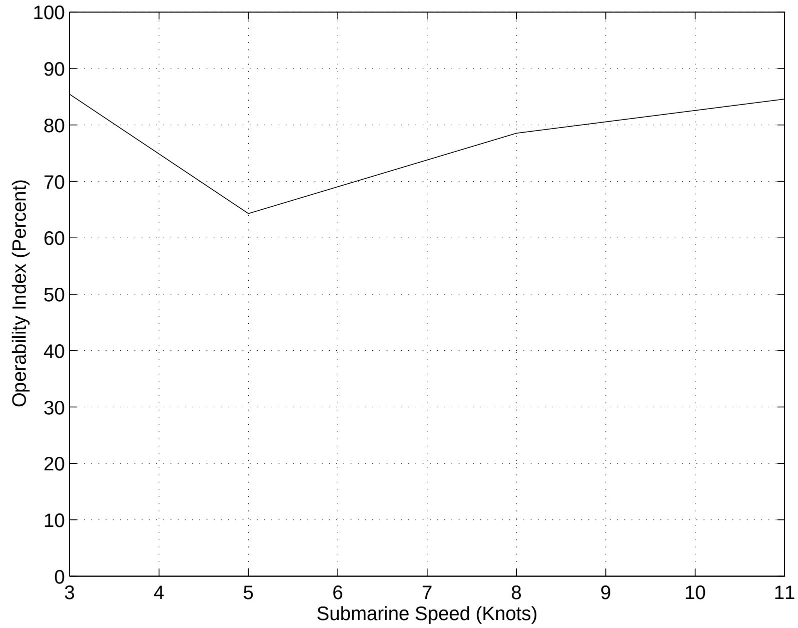

Figure 61. OI vs. Submarine Speed Plot at 4*D* depth

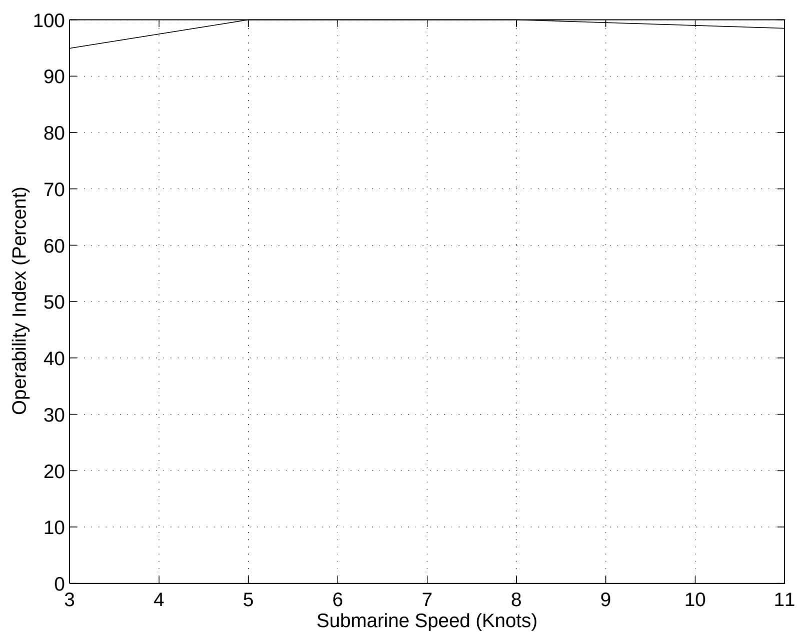

Figure 62. OI vs. Submarine Speed Plot at 4.5*D* depth

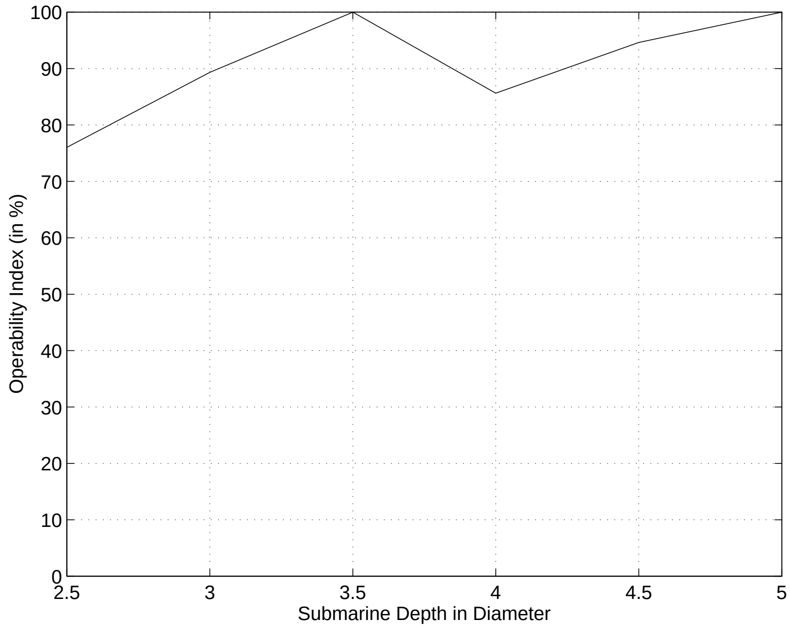

Figure 63. OI vs. Submarine Depth in Submarine Diameters at 3 Knots

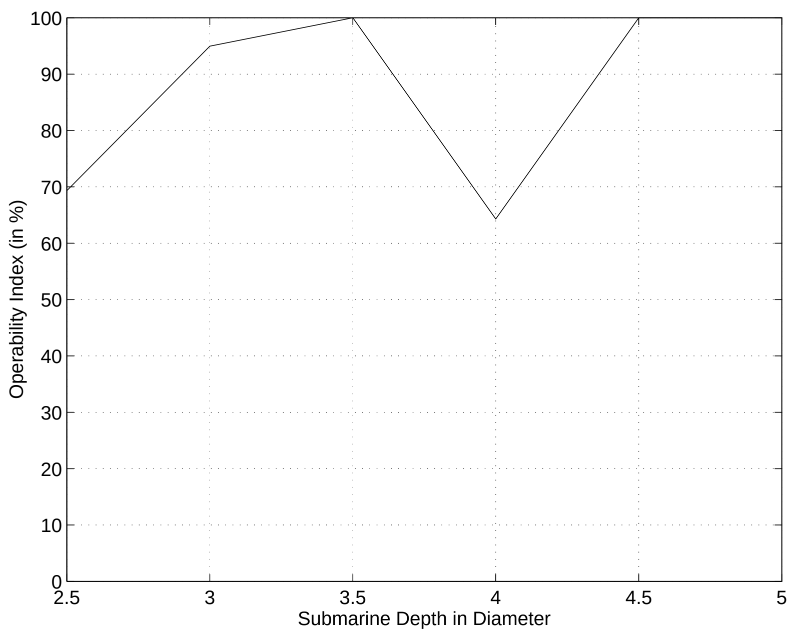

Figure 64. OI vs. Submarine Depth in Submarine Diameters at 5 Knots

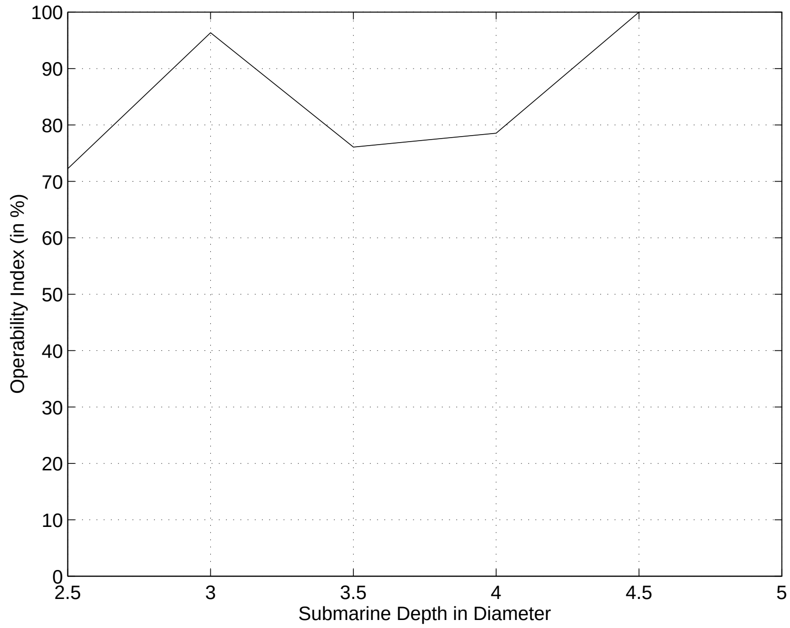

Figure 65. OI vs. Submarine Depth in Submarine Diameters at 8 Knots

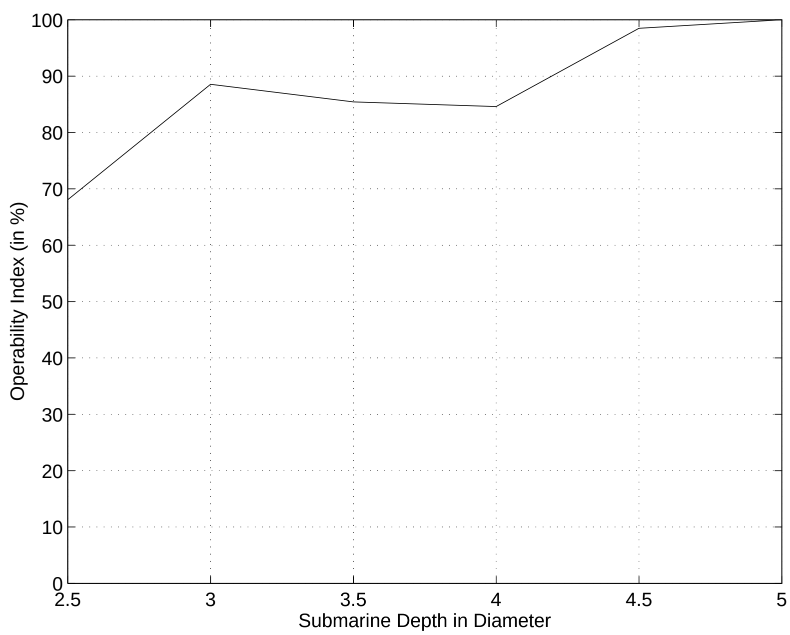

Figure 66. OI vs. Submarine Depth in Submarine Diameters at 11 Knots

D. RESULTS OF COMBINED CRITERIA

Results for both criteria combined are presented in Figures 67 through 100. The individual conclusions that were drawn previously continue to hold in this case as well. It appears that certain selections for speed and operating depth may result in higher values for the operability index. It should be mentioned, however, that this depends on the relative magnitude of the individual criteria, N_{p1} and N_{p2}. As an example, consider Figure 98. The overall operability index at 5 knots and depth 4.5 diameters appears to be less than 10%. As Figure 84 demonstrates, however, this is entirely due to the periscope submergence criterion violations. If this were of no concern in this case, the operability index would be raised to 100% as shown in Figure 62.

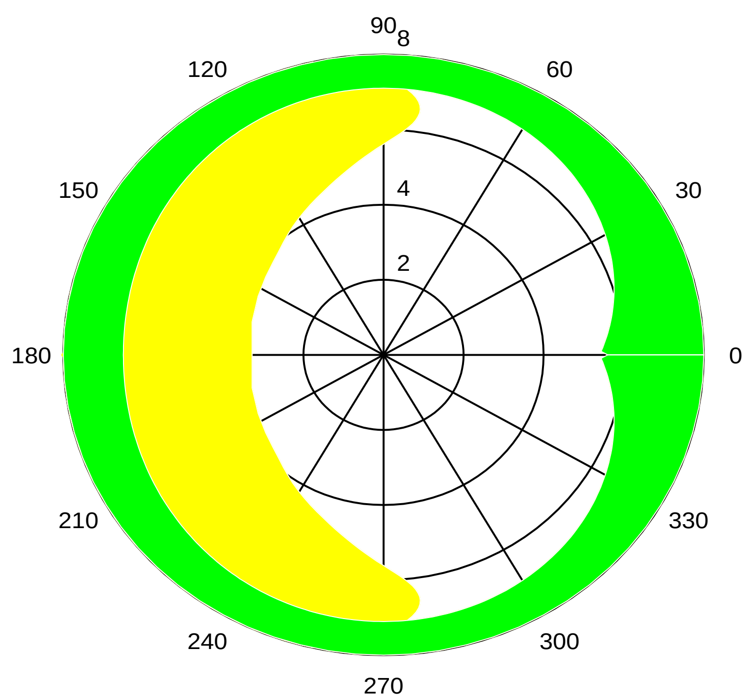

Figure 67. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=2.5D

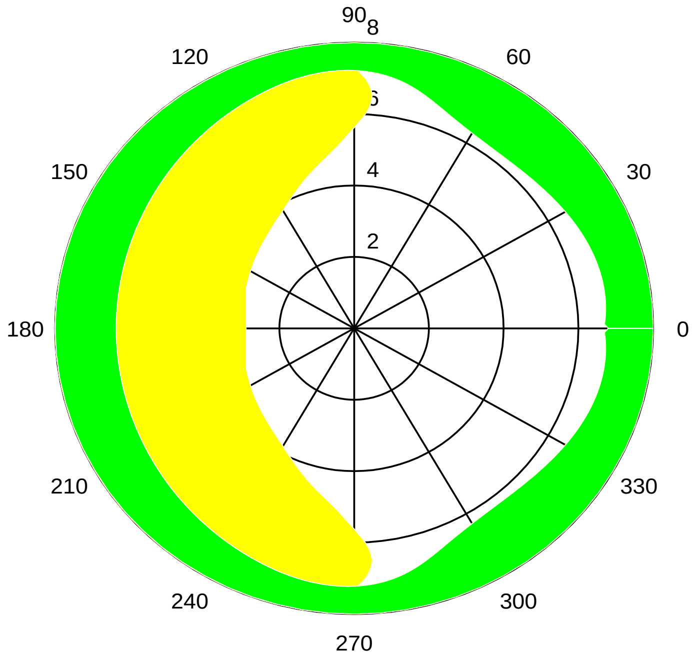

Figure 68. Sea state-polar plot, showing SOE for a submarine *U*=5 Knots, *h*=2.5*D*

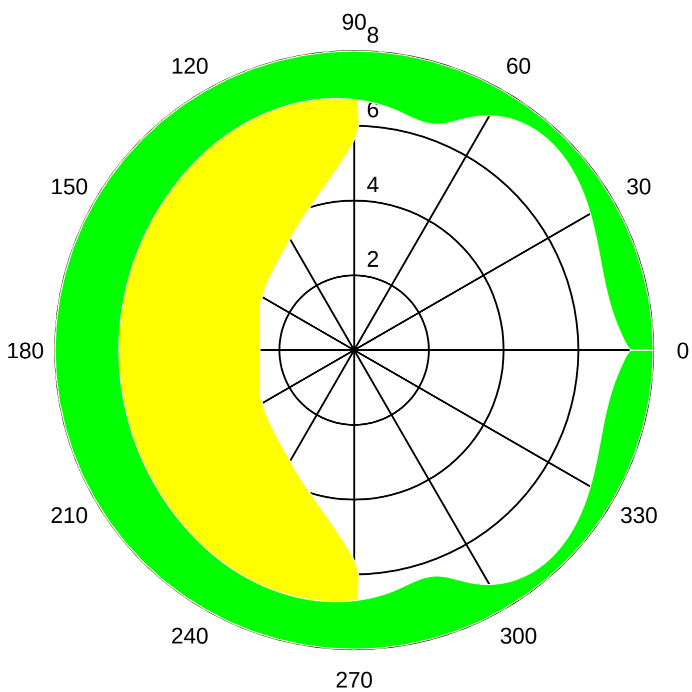

Figure 69. Sea state-polar plot, showing SOE for a submarine *U*=8 Knots, *h*=2.5*D*

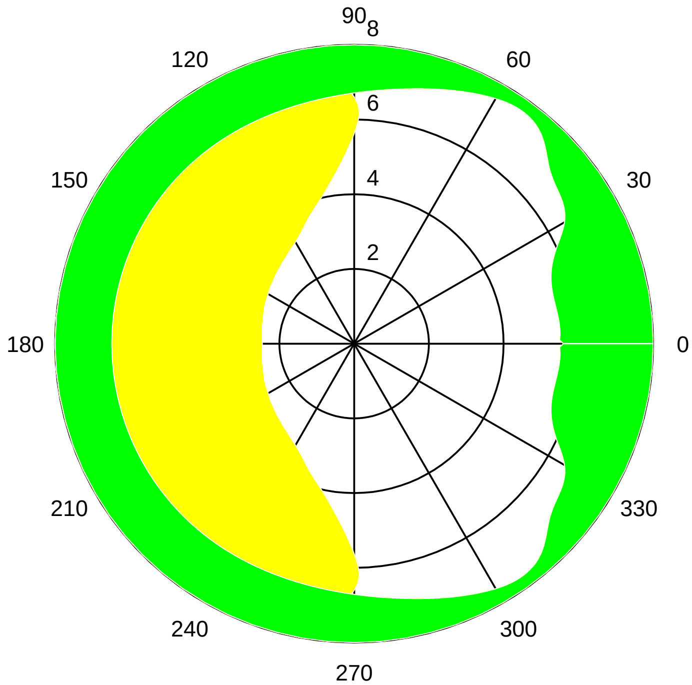

Figure 70. Sea state-polar plot, showing SOE for a submarine *U*=11 Knots, *h*=2.5*D*

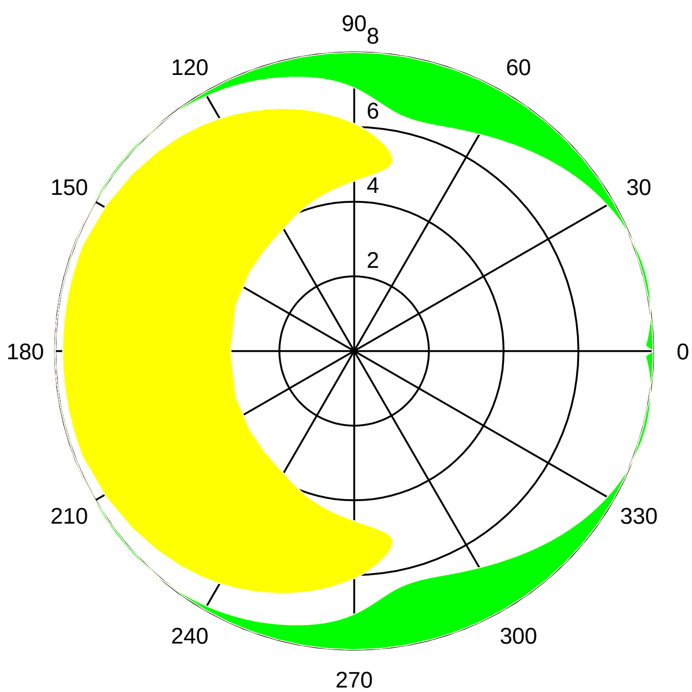

Figure 71. Sea state-polar plot, showing SOE for a submarine *U*=3 Knots, *h*=3*D*

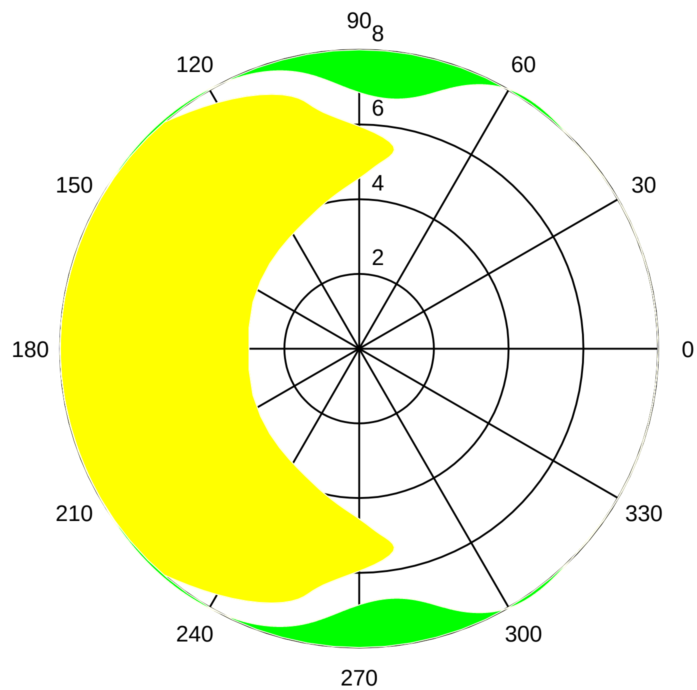

Figure 72. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=3D

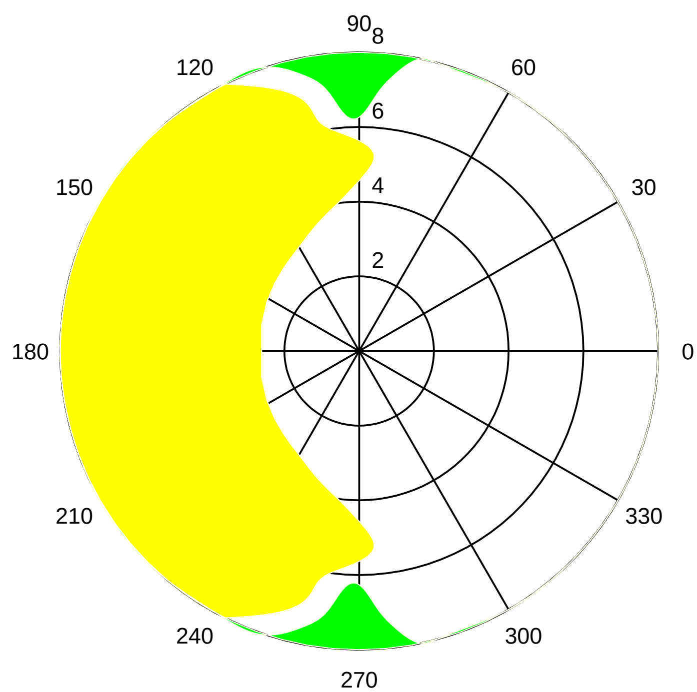

Figure 73. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=3D

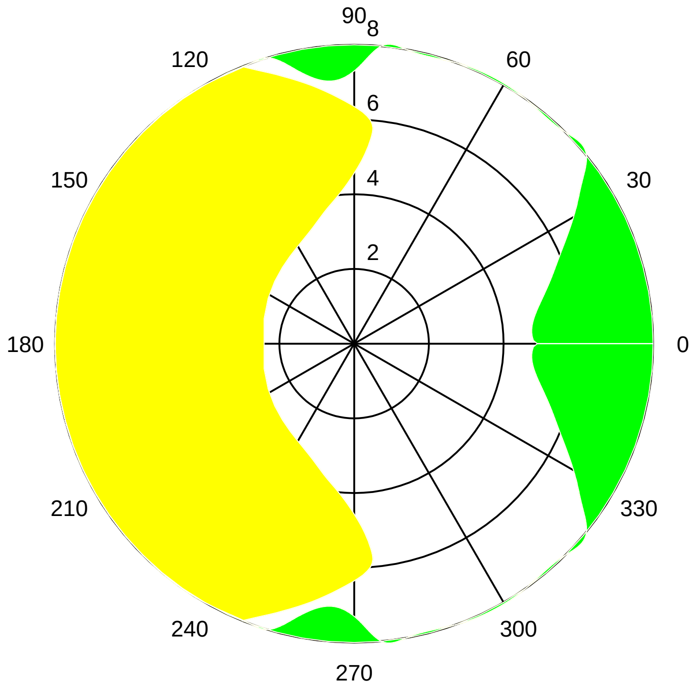

Figure 74. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=3D

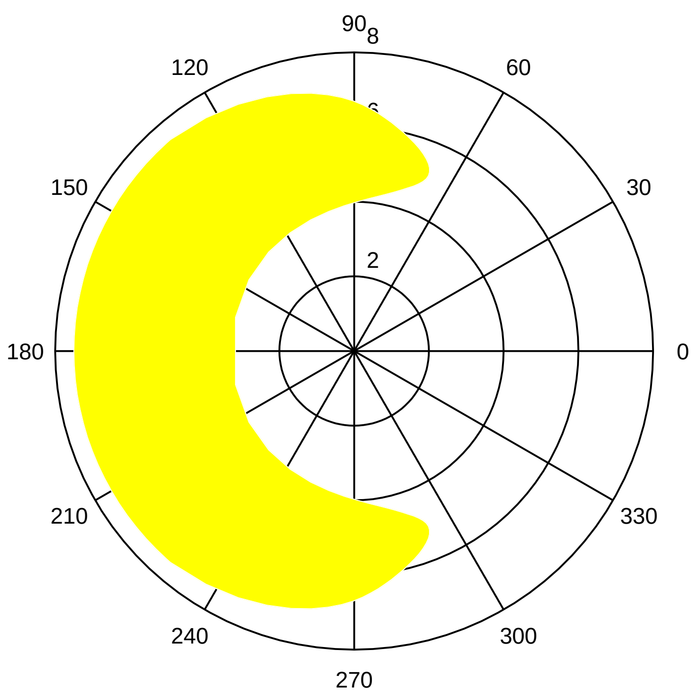

Figure 75. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=3.5D

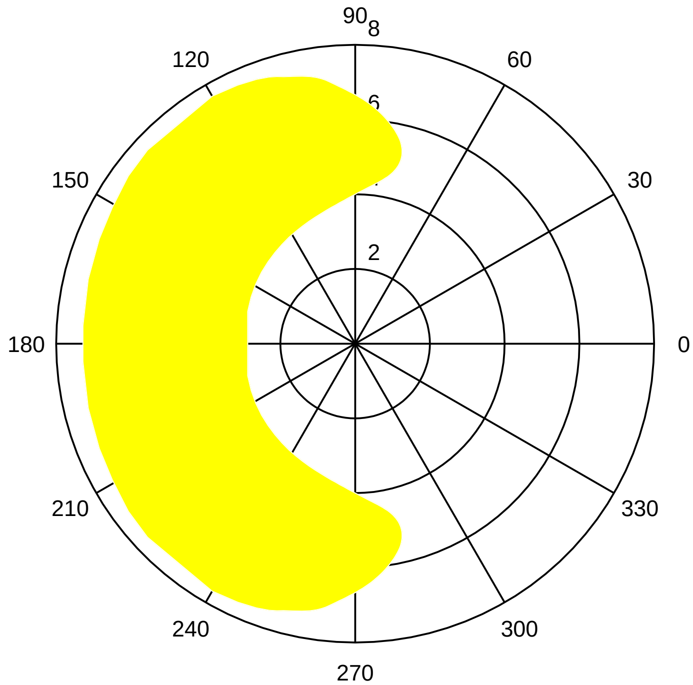

Figure 76. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=3.5D

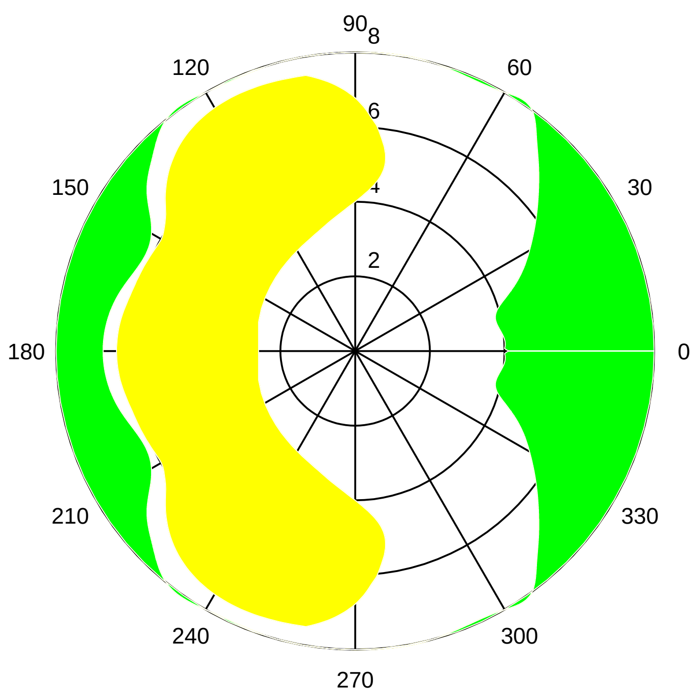

Figure 77. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=3.5D

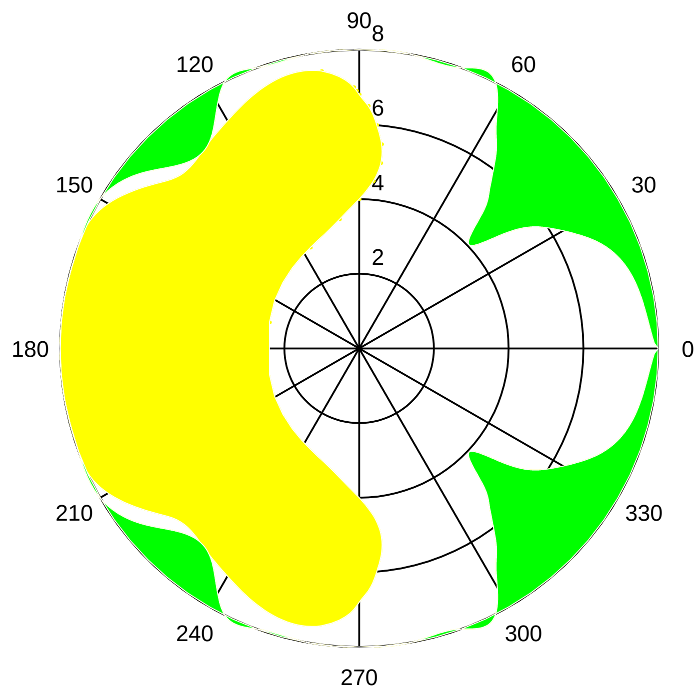

Figure 78. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=3.5D

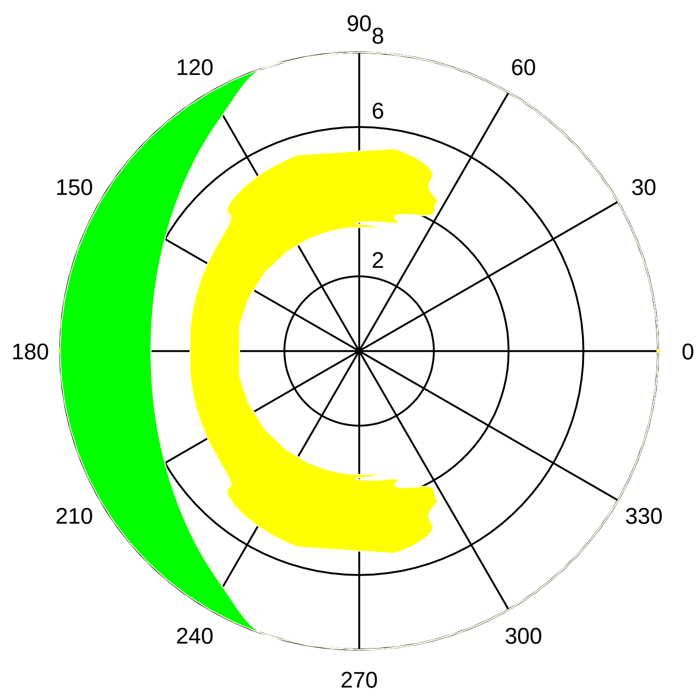

Figure 79. Sea state-polar plot, showing SOE for a submarine U=3 Knots, h=4D

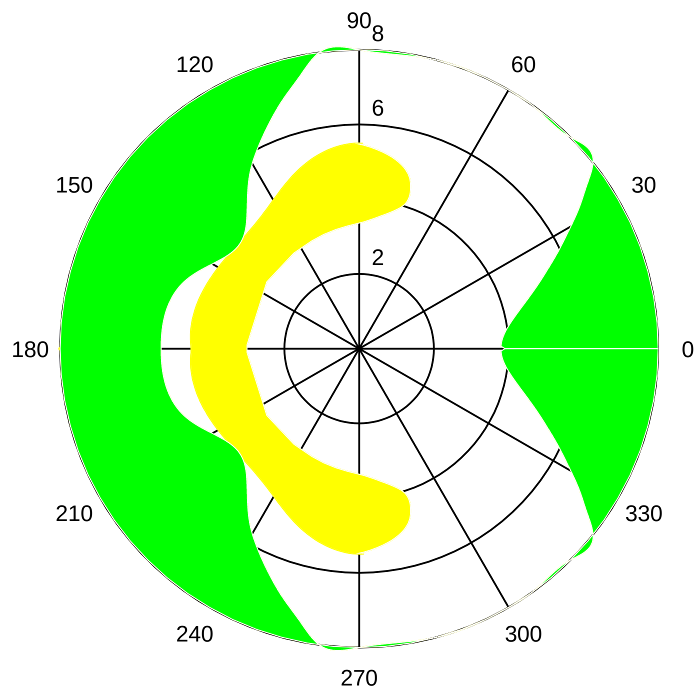

Figure 80. Sea state-polar plot, showing SOE for a submarine *U*=5 Knots, *h*=4*D*

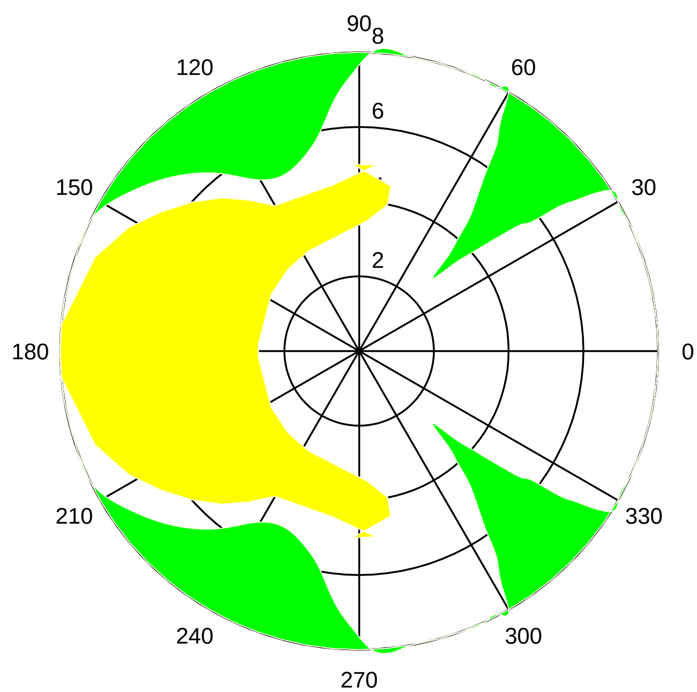

Figure 81. Sea state-polar plot, showing SOE for a submarine *U*=8 Knots, *h*=4*D*

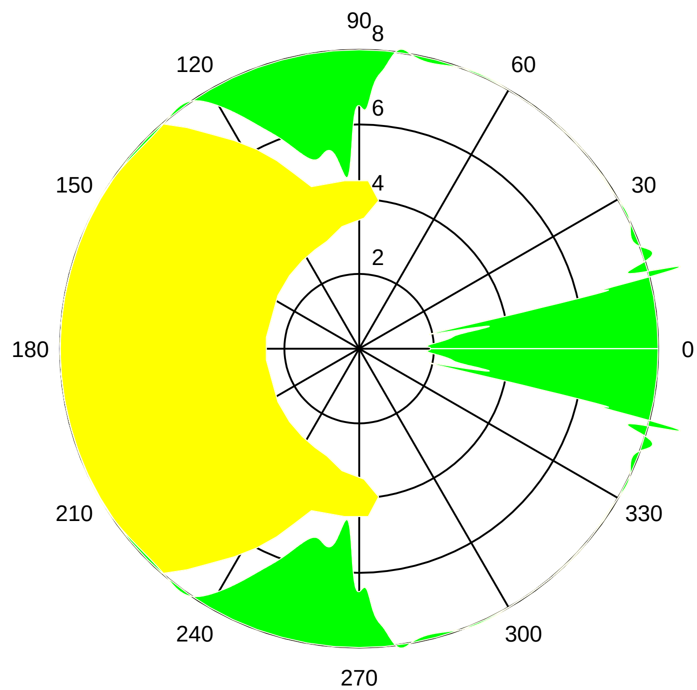

Figure 82. Sea state-polar plot, showing SOE for a submarine *U*=11 Knots, *h*=4*D*

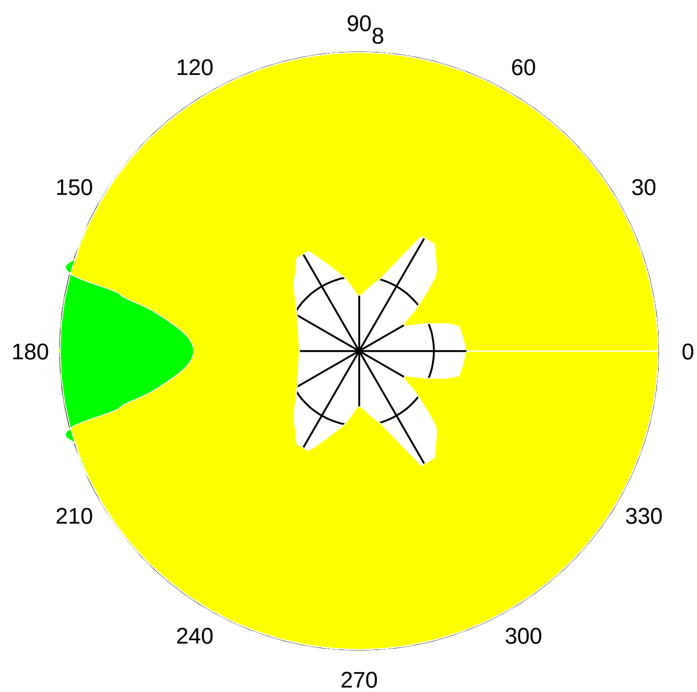

Figure 83. Sea state-polar plot, showing SOE for a submarine *U*=3 Knots, *h*=4.5*D*

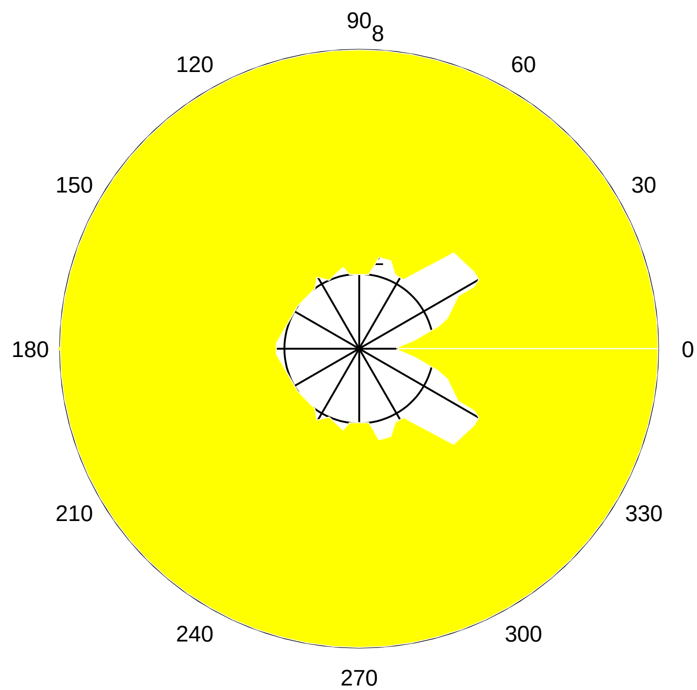

Figure 84. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=4.5D

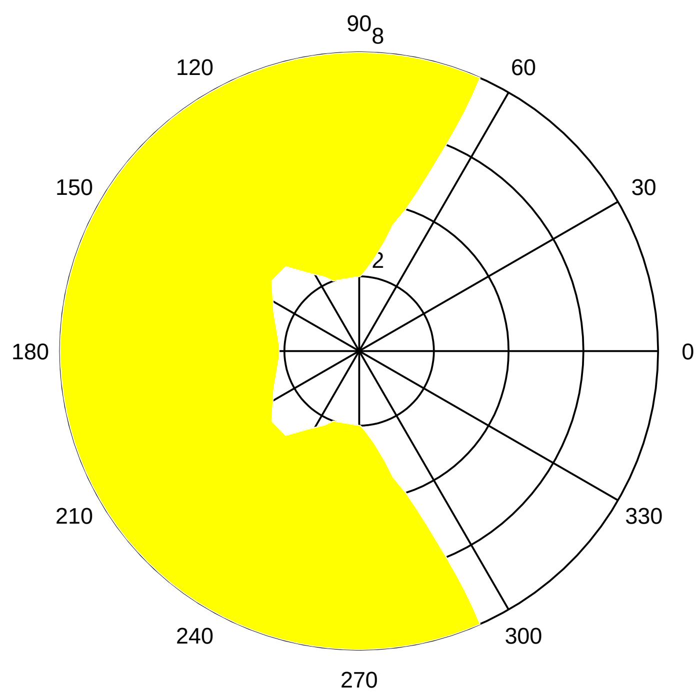

Figure 85. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=4.5D

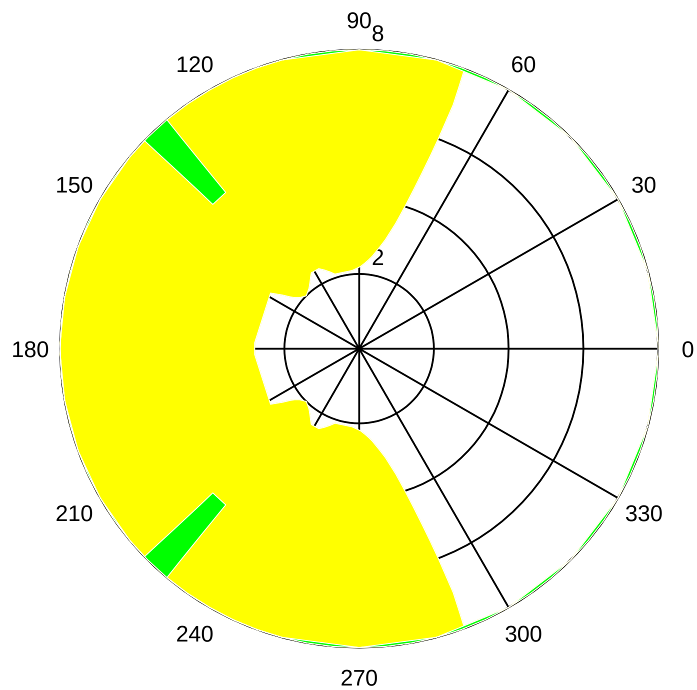

Figure 86. Sea state-polar plot, showing SOE for a submarine *U*=11 Knots, *h*=4.5*D*

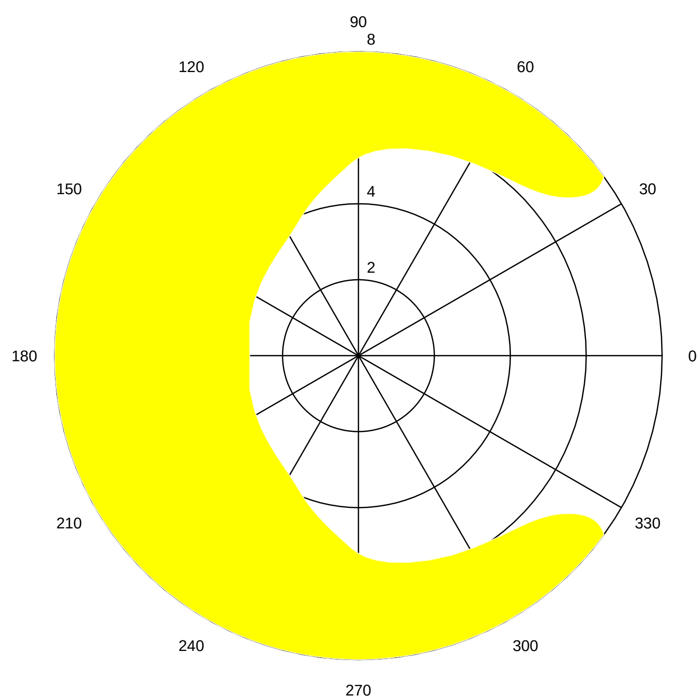

Figure 87. Sea state-polar plot, showing SOE for a submarine *U*=3 Knots, *h*=5*D*

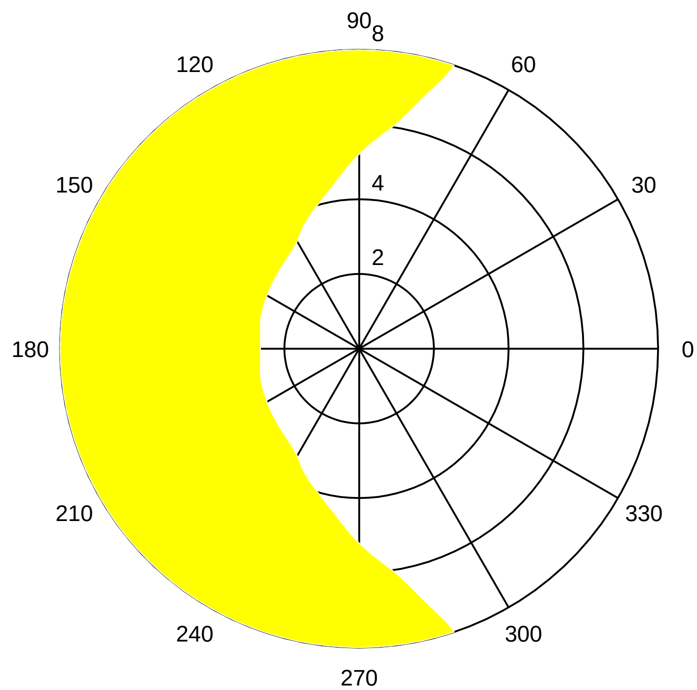

Figure 88. Sea state-polar plot, showing SOE for a submarine U=5 Knots, h=5D

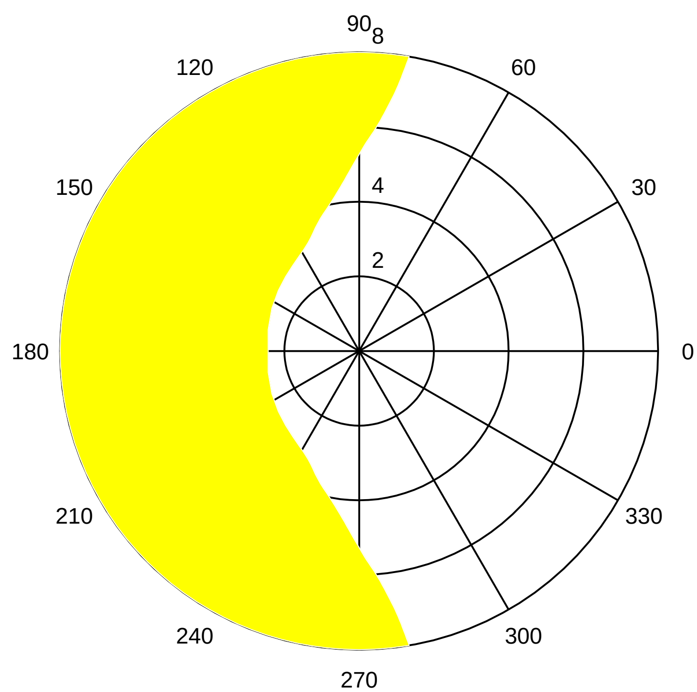

Figure 89. Sea state-polar plot, showing SOE for a submarine U=8 Knots, h=5D

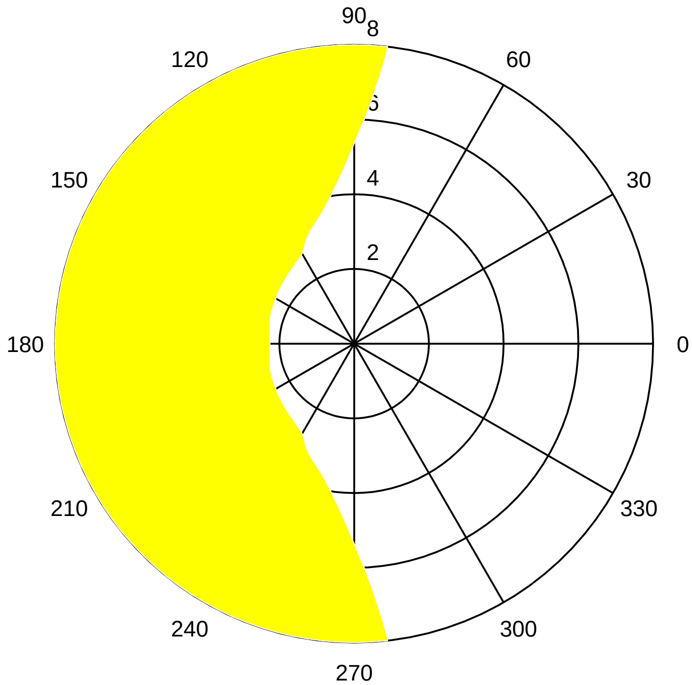

Figure 90. Sea state-polar plot, showing SOE for a submarine U=11 Knots, h=5D

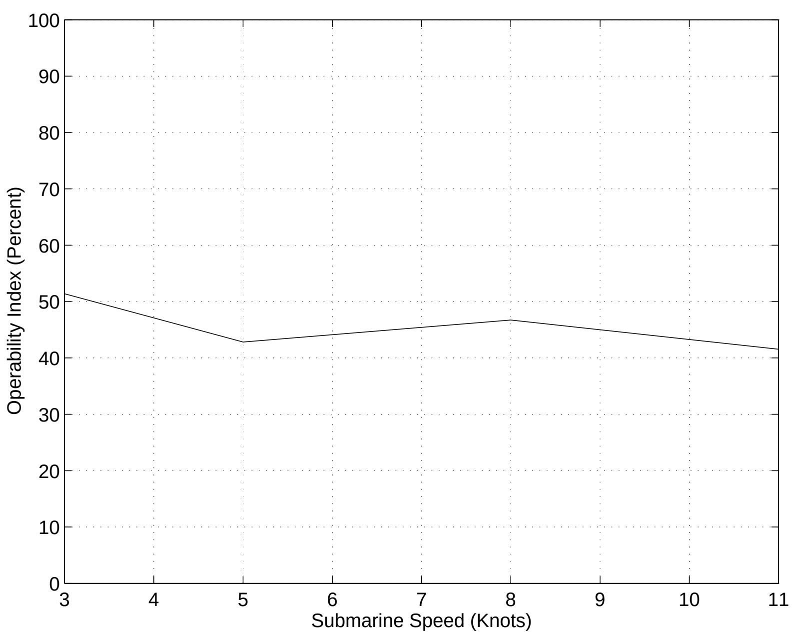

Figure 91. OI vs. Submarine Speed Plot at 2.5D depth

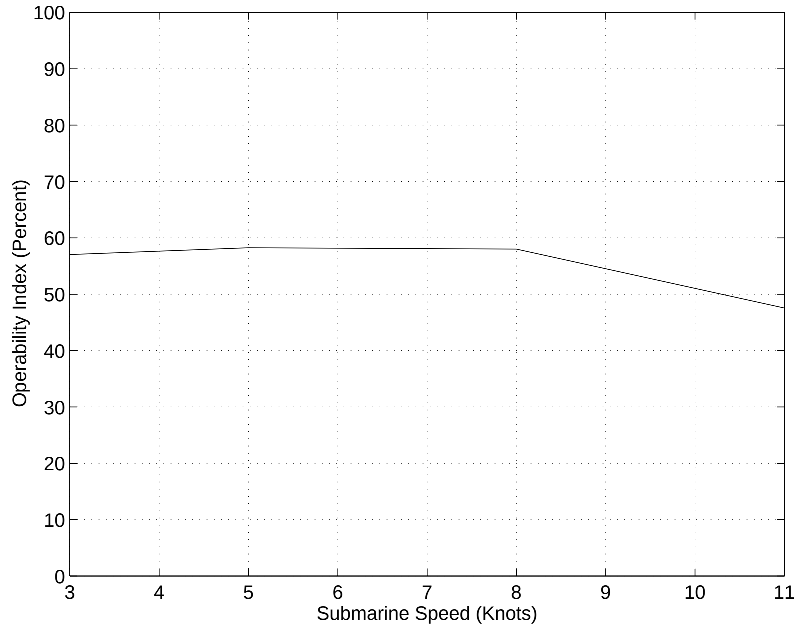

Figure 92. OI vs. Submarine Speed Plot at 3*D* depth

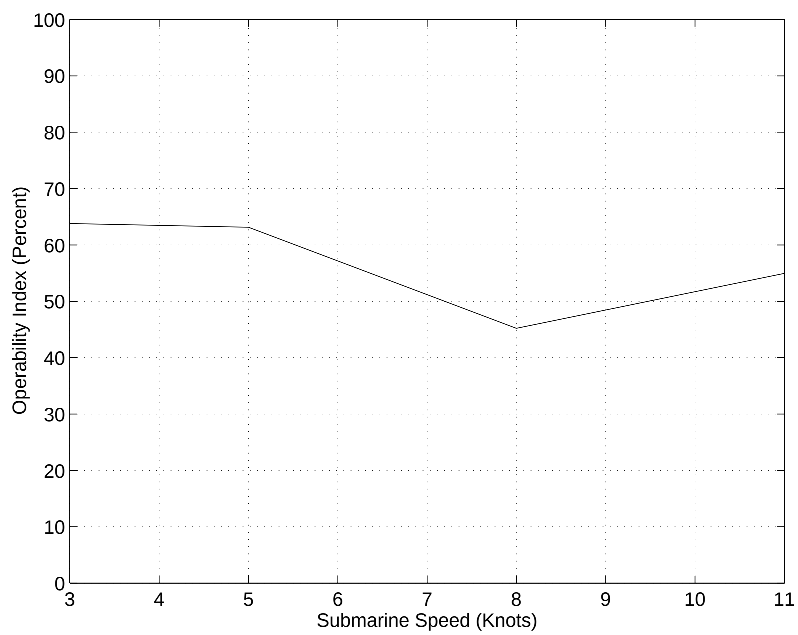

Figure 93. OI vs. Submarine Speed Plot at 3.5*D* depth

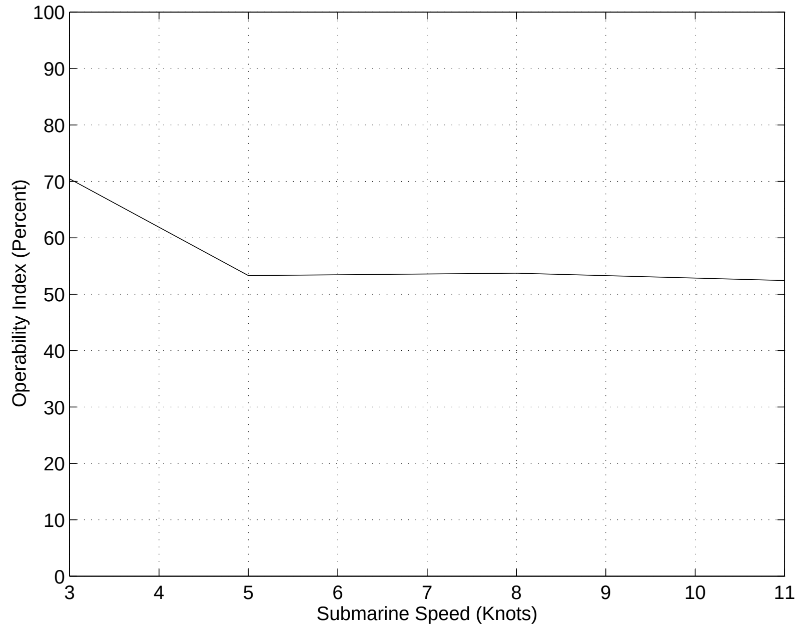

Figure 94. OI vs. Submarine Speed Plot at 4*D* depth

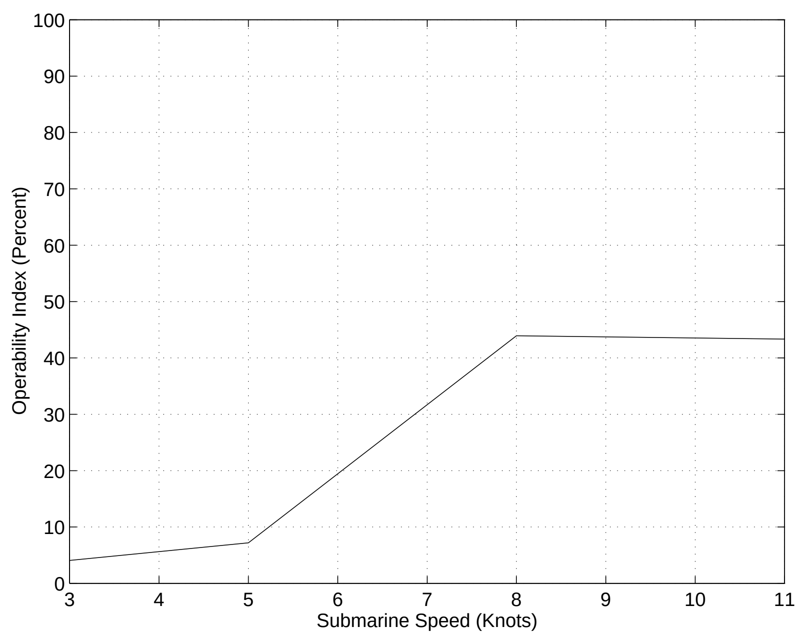

Figure 95. OI vs. Submarine Speed Plot at 4.5*D* depth

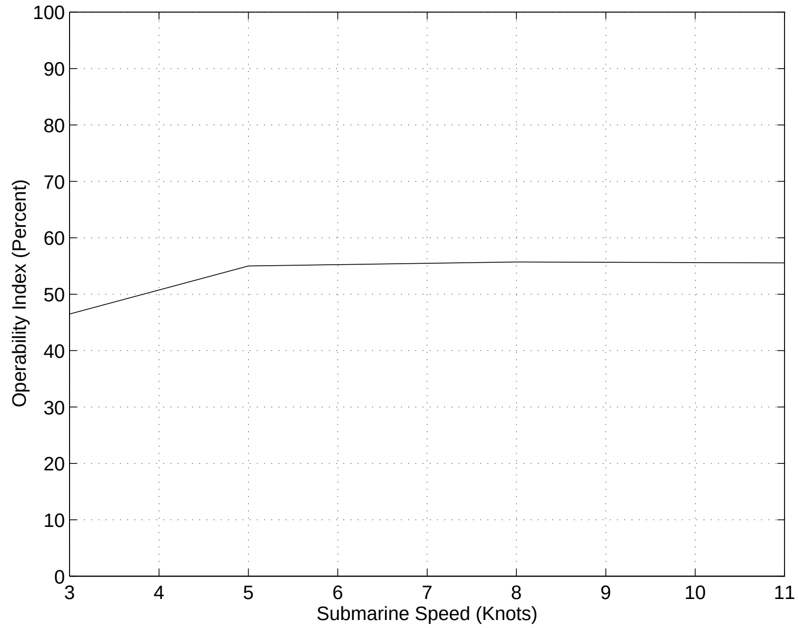

Figure 96. OI vs. Submarine Speed Plot at 5*D* depth

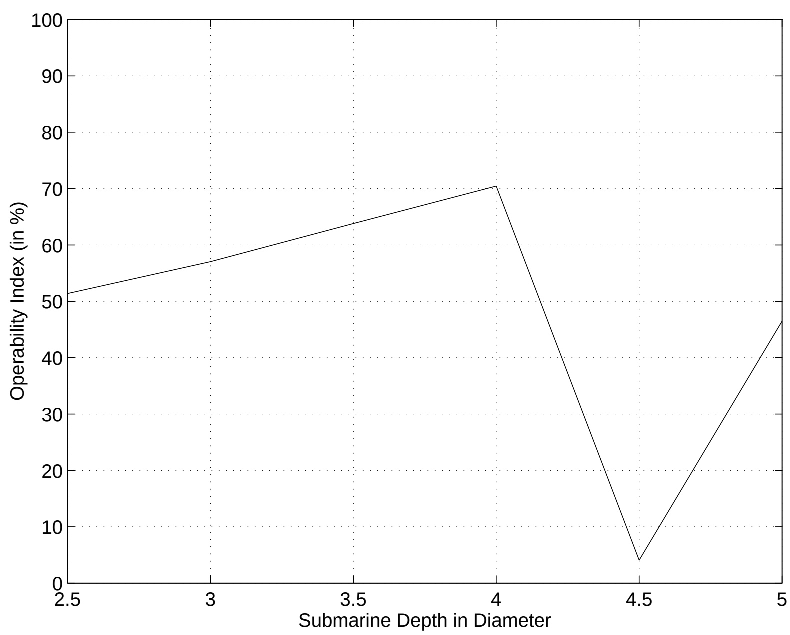

Figure 97. OI vs. Submarine Depth in Submarine Diameters at 3 Knots

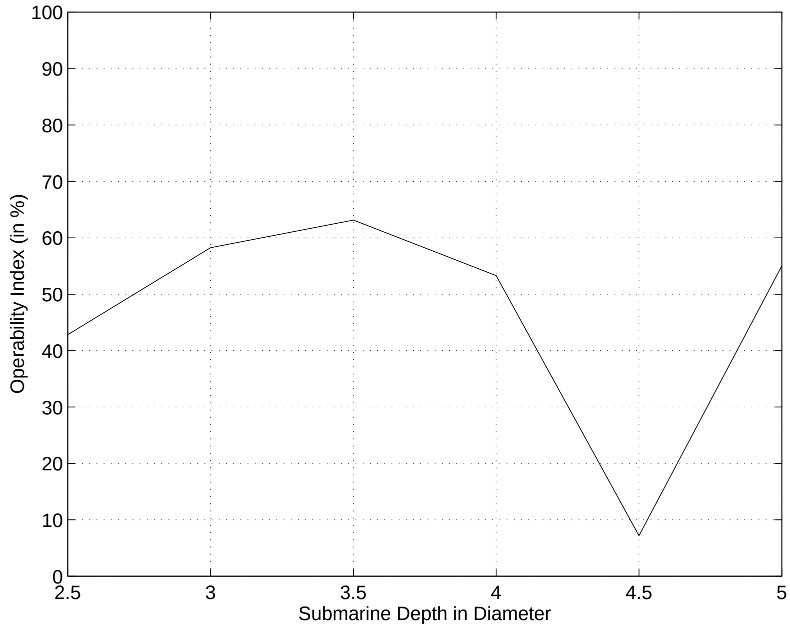

Figure 98. OI vs. Submarine Depth in Submarine Diameters at 5 Knots

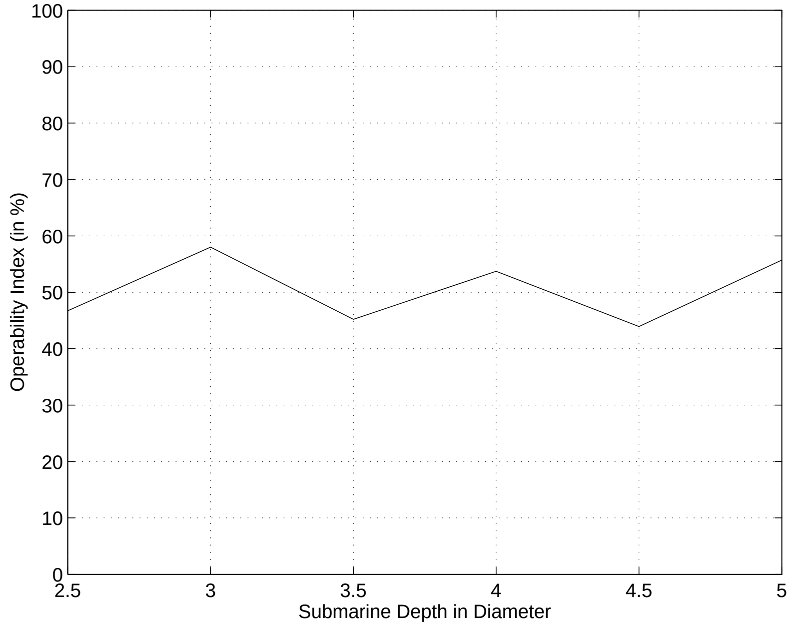

Figure 99. OI vs. Submarine Depth in Submarine Diameters at 8 Knots

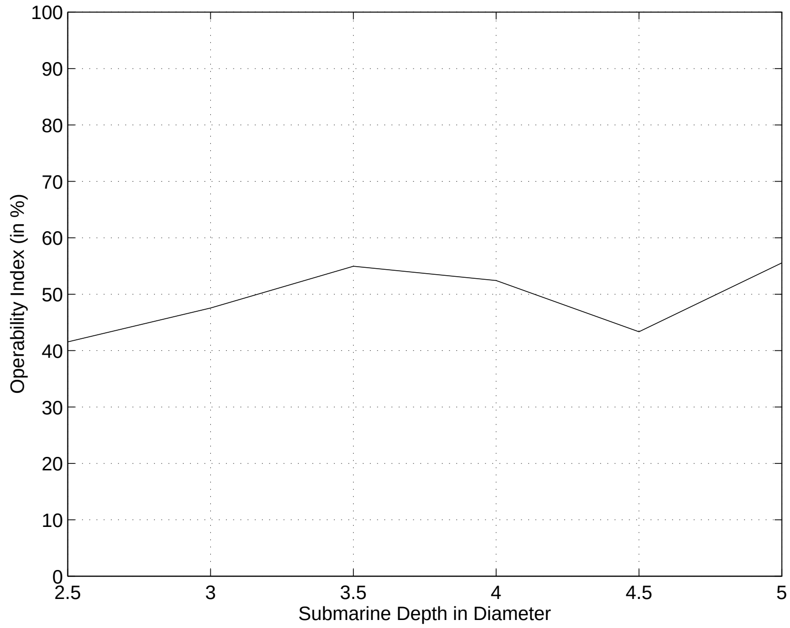

Figure 100. OI vs. Submarine Depth in Submarine Diameters at 11 Knots